DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY CA 93943-5101

Project Report

Mobile Treatment Modules for the Rhode Island Environmental Training Center

Submitted to Professor C. Poon
Special Project CVE 591
University of Rhode Island

Submitted by
David Herriott

In partial Fulfillment
of the Requirements for
the Degree of
Master of Science in Engineering

Department of Civil and Environmental Engineering
University of Rhode Island
Kingston, RI 02881
December 1994

T1005
K4994
c.1

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY CA 93943-5101

Table of Contents

Page

1. Introduction 1
   1.1 Background 1
   1.2 Objectives 3
   1.3 Definition 3
2. Mobile Treatment Module Concept 5
   2.1 Mobile 5
   2.2 Modular 6
3. Contaminants of Concern 6
4. Other Design Considerations 8
   4.1 Applicable 8
   4.2 Educational 8
   4.3 Reliable 9
   4.4 Flow Capacity 9
5. Treatment Options 10
6. Recommended Modules 11
   6.1 Granular Activated Carbon Adsorption 11
   6.2 Prefilter 12
   6.3 Biodegradation Reactor 12
   6.4 Carbon Regeneration 14
   6.5 Advanced Oxidation 17
   6.6 Air Stripping 19
   6.7 Off-Gas Treatment 19
   6.8 Chemical Precipitation 20
   6.9 Electric Generator 20
   6.10 Water Storage 21
7. Design of GAC Module 21
   7.1 Carbon Selection 22
   7.2 Adsorber Design Parameters 23
   7.3 EBCT and Carbon Use Rate Predicted By CPHSDM ... 26
   7.4 Adsorber Configuration 32
   7.5 Other Design Considerations 34
      7.5.1 Head Loss Vs. Hydraulic Loading Rate 34
      7.5.2 Backwash Flow Rate 35
      7.5.3 Underdrain System 36
      7.5.4 Operating Pressure And Air/Vacuum Releases 36
      7.5.5 Carbon Transport 36
      7.5.6 Construction Materials 37
      7.5.7 Special Features --- Biological Reactor. 37
   7.6 Recommended Adsorber Design Values 40
   7.7 Pipes, Valves, and Pumps 41
   7.8 Description of Operation 44
      7.8.1 Operations 45
      7.8.2 Description 45
   7.9 Electrical System 47
   7.10 Structural 48
   7.11 Monitoring and Controls 49
   7.12 Cost and Weight Estimates 50
8. Summary and Recommendations 51

References 52
Appendices 56
A. Operating Vessel Pressure Calculation 57
B. Table of Minimum Stanton Numbers Required for Constant Pattern Condition as Function of Bi for Various 1/n Values 58
C. Parameters For Empirical Equation That Describes Solutions To CPHSDM For a Fixed Bed Reactor 59
D. Example Calculation Using CPHSDM Solution 60
E. Pipes, Pumps, and Valves 62
F. Drawings 68
Drawing M-1, Combined Sections 69
Drawing M-2, Auxiliary Section Detail 70
Drawing M-3, Adsorber Section Detail 71
Drawing A-1, Adsorber Vessel 72
Drawing A-2, Adsorber Vessel End Assembly Detail 73
Drawing S-1, Structural Plan View Combined Sections 74
Drawing S-2, Structural Plan View Skid Detail .. 75
Drawing S-3, Side View Adsorber Section 76
Drawing S-4, Side View Auxiliary Section 77
Drawing S-5, End View Auxiliary Section 78
Drawing S-6, End View Adsorber Section 79
Drawing E-1, Electrical Layout 80
G. Cost and Weight Estimate 81

Figures

Page

Figure 6.1 Infrared Incineration MTM 16
Figure 6.2 Sketch of Ultrox UV/Oxidation Treatment System 18
Figure 7.1 Mass Transfer Zone in Adsorption Bed 24
Figure 7.2 Simulated Breakthrough Curve For 1,2-dichloroethane Using CPHSDM 25
Figure 7.3 Pressure Drop VS. Hydraulic Loading For F-400 .34
Figure 7.4 Expansion of Filtrasorb 400 Carbon Bed 35
Figure 7.5 Hybrid GAC Reactor Flow Diagram 39

Tables

Table 3.1 Ground Water Contaminants of Concern - Allen Harbor Landfill.....7
Table 5.1 Summary of Suitability of Treatment Technologies.....11
Table 7.1 Estimates of GAC Use In Controlling Common Groundwater Contaminants 31
Table 7.2 Downflow GAC Adsorber Design Data 40
Table 7.3 Expanded-Bed Adsorber Design Data 41
Table 7.4 Pump/System Operating Point Specifications (P5 & P6).....42
Table 7.5 Pump/System Operating Point Specifications (P2) 42
Table 7.6 Expanded Bed Pump/System Operating Point Specifications (P4).....43
Table 7.7 Carbon Supply Pump/System Operating Point Specifications (P3).....44
Table 7.8 Backwash Pump/System Operating Point Specifications (P1).....44
Table 7.9 Summary of Circuits.....48

1. Introduction

1.1 Background

Groundwater pollution can result from many activities, including leaching from landfills and abandoned dump sites, accidental spills of chemicals or waste materials, improper underground injection of liquids, and leakage from faulty septic systems or underground storage tanks. Discoveries of aquifer pollution from man's waste disposal practices are increasing. At the same time, demand for groundwater is increasing as our population grows and sources of surface water diminish. It is no longer practical to simply curtail use of aquifers when contaminants are found. Current regulations are driving the development of appropriate technologies for aquifer cleanup and forcing responsible parties, business, and government agencies to take action to clean up contaminated aquifers .

The traditional design/construction process for remediation of contaminated sites is expensive and lengthy. During the past decade, potentially responsible parties (PRPs) have delayed cleanup of contaminated sites until pushed by regulatory agencies or legal actions. There are many reasons for the reluctance of PRPs to initiate cleanup including: assumed liability, limited experience with certain remediation technologies, uncertainties if regulated cleanup standards can be achieved, and the key factor in almost any business decision, cost.

Faced with a staggering cleanup bill, many responsible parties choose to delay the inevitable in hopes that their attorney's will be able to make the problem "go away" or negotiate reduced liability/cost. However, once a site is elevated to the National Priority List (NPL) and gains Superfund status, responsible parties lose control over the cleanup. Once on the NPL, cleanup of the site is carried out under the stringent guidelines of the Comprehensive Environmental and Cleanup Liability Act (CERCLA) which means a remedial investigation/feasibility study(RI/FS) and record of decision (ROD) must be completed. Additionally, each step will

require government inspection/approval, work schedules, and other extra reporting requirements. This, in-turn, greatly increases the cost of site restoration. Today, the average site cleanup cost is estimated at $20 to $30 million.[17]

Historically, many years of measuring and studying the specific site conditions and contaminant characteristics are performed to select the "best solution" for a specific site. During this period (often exceeding 10 years) the contaminant can migrate considerable distance requiring a larger area to be remediated once a final remedy is eventually implemented. Also, the traditional design and use of site specific treatment facilities increases the cost of cleanup since the equipment cannot be readily transported to another location to be used again.

Widespread corporate belt-tightening and large reductions in Department of Defense (DOD) funding are forcing many responsible parties to find alternative approaches to site remediation. A way to reduce cost is to pursue early cleanup before Uncle Sam steps in to help out and before contaminates travel into a wider spectrum of the environment requiring a greater cleanup effort. A key to being able to act quickly is to have proven, easily transportable, treatment equipment ready to go.

A recent trend, is to fast track the remediation process by employing mobile units which can be quickly set up and put into operation to address the contamination problem with the speed and urgency it deserves. The traditional study, design, and construction of a site-specific treatment process simply takes too long. Mobile units can serve as an interim treatment system to expeditiously control migration, and address public health and safety concerns while time and technology work together for a permanent cost-effective remediation plan. Mobile units may be designed to work as a single unit or combination with other units to form a treatment train tailored to treat a particular situation. These units can be easily moved from one spill location to another to spread the capital investment costs over several cleanup sites. In some situations, these mobile units may provide both initial treatment and long range permanent remediation.

The former Davisville-Quonset Point Naval Complex is in the final stages of base closure. The base contains areas where contaminant migration and remediation technologies can be studied in ground water, soil, and coastal environments. The University of Rhode Island (URI) plans to establish the "Rhode Island Environmental Education/Training Consortium" with a training center housed in an old Battalion Headquarters facilities. URI has received funding through the "DOD Environmental Scholarship/Fellowships and Grants Program" to help finance the center. As part of the training center, URI plans to use prototypes to provide "hands-on" experience for students in the operation of various types of remediation technologies.

1.2 Objectives

This project has three objectives: First, to discuss and further define mobility and the modular building block concept as applied to ground water treatment. Second, to provide recommendations for Mobile Treatment Modules (MTM's) for use at the "Rhode Island Environmental Education/Training Consortium", Training Center which may be employed to expedite ground water treatment efforts at DOD installations. And finally, to present a conceptual design of an activated carbon adsoption MTM.

1.3 Definition

While preparing to write this paper, I found many people seem to use the terms "treatment" and "remediation" synonymously. I sought an explanation of these terms. The best explanation I found concerning these two concepts was offered by Neyer and Morello. [29]

Treatment is the application of a technology to a specific medium such as air, water or soil. *Remediation* is the cleaning of an entire environment such as a wetland, industrial site, or Superfund site. We treat ground water, but we remediate an aquifer.

Spilled contaminants typically exist in four phases.[3] The free phase contamination is found migrating through the soil or floating

on top of ground water. Contamination that adheres to the soil is called the adsorbed phase. The soluble or dissolved phase contamination is found in the ground water. Vapors that exists in the soil are called the vapor phase. Most treatment processes use water or air to transport the contaminants from the aquifer, soil, and vadose zone. We have a good understanding of how to treat air, water, and soil to remove/destroy many contaminants, but struggle to overcome the technical complexity and limitations associated with remediating a site. This is because residual concentrations of the contaminant in the ground water or soil often reach asymptotic levels which are greater than the current required cleanup standard. This explains why we can achieve 99.999 % removal of a certain contaminant from extracted ground water, but fail to remediate the site. It also helps explain the reluctance of responsible parties to sink large sums of money into treatment processes that will never reach the final remediation goal. In fact, it has caused many to ask the question: "Is it technically feasible to restore contaminated ground water at all sites to current maximum containment level (MCL) standards "?[12,39] Currently, the House Public Works and Transportation Committee and Senate Environmental and Public Works Committee are considering this question and are looking closely at changing the current cleanup standards for superfund sites to a feasible cleanup level for each specific site.[27]

In the context of this paper, the focus will be on ground water *treatment* technologies with the understanding that ground water treatment is quite often only one element of a successful "synergistic" approach to site remediation combining treatment of all phases of the contamination: free phase, adsorbed phase, dissolved phase and vapor phase. And that by acting quickly, ground water treatment can slow or stop plume migration thus reducing the long term remediation effort and cost.

2. Mobile Treatment Module Concept

In order to control plume migration, treatment should begin as soon as possible. If a site specific, stationary treatment facility is to be employed, many steps must take place before the process is put in operation: technology(s) selected; site preparation; process design; equipment selection; purchase of materials; and construction. By having all of the necessary equipment pre-assembled on a portable platform, mobile units can be dispatched for site remediation where a spill or leak has occurred and treatment can begin as soon as wells are developed and the mobile unit(s) is on site.

This concept is not new. The military keeps a large supply of pre-positioned war inventory for the sole purpose of rapid deployment. Many commercial manufactures have grasped this idea and now offer their treatment equipment configured on mobile platforms.

2.1 Mobile

In order for a process to be mobile it must be self-sufficient, portable and delivered to the site ready-to-use so that it can be rapidly deployed and put into operation. The transportability criteria is easily met by designing each module to fit on platforms (skids) which fit on trailers that can be transported by truck, rail, ship, or military aircraft. The maximum size of a trailer mounted, truck-transportable unit is governed by the over-the-road size and weight limitations. In general, size restrictions are a length of 45 ft, width of 12 ft, height of 12 ft, and weight of 64,000 lb.[36] For purposes of this project, the size will be limited to a width of 8 ft, length of 40 ft, height of 9 Ft and a weight of 50,000 lb allowing over-the road transportation on a 3 Ft. high lowboy trailer.

Self-sufficiency is defined as being able to operate independently without any additional support. In this case two criteria will be used: First, in order for the unit to be self-

sufficient there should be no required utilities at the site. The process must be capable of operating from a single power source (mobile electric generator or line service, if available). Second, the process must require minimum off-site disposal of contaminated material and require a minimum amount of consumables. To do so, the process(s) should provide complete treatment and not simply be a volume reduction measure requiring ultimate disposal/treatment off-site. This follows the US Environmental Protection Agency's (EPA) current guidelines showing a clear preference for treatment technologies that reduce or eliminate a hazard rather than transferring it to a different medium.[41]

2.2 Modular

Due to the complex compositions of most ground waters, no one unit operation is capable of removing all of the contaminants present. Usually it is necessary to combine several unit operations (modules) into a series of treatment processes (train) to effectively remove the contaminants. There is no set way to configure these unit operations. In certain situations a given module should proceed another and in others it should be the last treatment step (GAC pre-filter Vs GAS polishing). Therefore, the modular concept allows flexibility to configure the required building blocks (modules) as necessary to treat a given ground water.

3. Contaminants of Concern

Although many contaminants could conceivably find there way into aquifers, the most common contaminants found in ground water at military installations include pesticides, petroleum products from underground storage tanks, solvents and metals from engine maintenance activities, ordnance, landfill leachate, and direct spillage or surface runoff of hazardous waste. These contaminants can be categorized into the following groups: inorganics, volatile

organic compounds, synthetic organic compounds, and other (pesticides and PCB's)

As an example, Table 3.1 lists contaminants of concern have been identified in the ground water at the former Davisville-Quonset Point Naval Complex and nearby Allen's Harbor Landfill. This list provides a good indication of the range of contaminants typically found in ground water with 1,1,1 trichloroethane and trichloroethylene usually being the most prevalent.[20,30]

Table 3.1 Ground Water Contaminants of Concern - Allen Harbor Landfill

Inorganics	Volatile Organics	Semivolatile Organics	Other
Aluminum	Acetone	Acenapthene	Dieldrin
Antimony	Benzene	Bis(2-chloroethyl) ether	
Arsenic	Chlorobenzene	BIS-chloroisopropyl) ether	
Barium	Dichloroethane 1,2	Dibenzofuran	
Beryllium	Dichloroethene 1,2	Dichlorobenzene 1,2	
Cadmium	Dichloropropane 1,2	Dichlorobenzene 1,4	
Chromium	Ethybenzene	Diethylphthalate	
Cobalt	Toluene	Dimethylphenol 2,4	
Copper	Trichloroethene	Fluorene	
Lead	Trichloroethanel, 1,1	Methylnaphthalene 2	
Manganese	Vinyl chloride	Methylphenol 2	
Mercury	Xylenes (Total)	Methylphenoal 4	
Silver		Naphthalene	
Thallium		Nitrophenol 4	
Vanadium		Oxybis	
Zinc		Phenol	

The two most prevalent sources of contaminants found on military installations are industrial maintenance facilities and underground storage tanks (UST's).[32] Maintenance facilities, such as aircraft maintenance facilities, used trichloroethylene (TCE) for degreasing metal parts. Lead and chromium have been discovered in waste waters released from metal plating and painting facilities, and an assortment of petroleum hydrocarbon compounds result from UST leakage.[30,35]

4. Other Design Considerations

In addition to being mobile, further criteria are required to narrow down the alternative technologies and design MTMs.

4.1 Applicable

The type of treatment technology depends primarily on the type of contaminant being removed. Common contaminants found in ground water have been categorized into the following groups: inorganics, volatile organic compounds, synthetic organic compounds, and others. While a single technology cannot efficiently destroy/remove all of these contaminants, some technologies are effective in treating a wide range of contaminants by making small changes in their operation.

The goal is to select technologies which when combined together in various configurations can provide an effective treatment train(s) to destroy all categories of contaminants normally found in ground water. Preference will be given to those technologies which show promise of treating a wide range of contaminants with small operational changes thus reducing costs and maximizing technology exposure for students.

4.2 Educational

Since the prototype modules are intended to be used at the "Rhode Island Environmental Education/Training Consortium", Training Center, special consideration should be given to enhance

the educational benefits of the equipment. In addition to being a functioning treatment process, the modules should be designed to allow students to explore "what-if" situations. The ability to change operating parameters and monitor the results is key to improving any process. Therefore, flexible piping arrangements to allow a variety of operating modes should be integrated into the design.

4.3 Reliable

In general, processes that are the most simple in design and operation are the most reliable. In selecting technologies for use as MTMs, preference will be given to conventional technologies which have been proven over time to give reliable results. However, the design of the modules should be flexible to allow the "what-if" scenario to be investigated, and in doing so, incorporate a few "not-so-conventional" processes.

4.4 Flow Capacity

Since the modules are designed to operate in series with each other, they need to be designed for the same flow rate. The optimum flow rate for a given situation is based on many variables such as physical properties of the aquifer, and the mode of operation. If the system is used to contain or reverse the direction of a large contaminated plume, the flow rate is much larger than it would be to treat a small perched water table. The modular, building block concept allows total flow rates to be customized for a particular situation by connecting treatment trains in parallel to met the required flow rate. A flow rate of 20 gpm will be used to design individual units (small enough to be mobile, but large enough to treat a small plume).

5. Treatment Options

A variety of groundwater treatment technologies have been employed to cleanup contaminated groundwater. Membrane processes are used to separate contaminates from water on the basis of their molecular weight and size, thus reducing the volume of contaminated water. Adsorption materials provide large surface areas to transfer contaminants from the liquid to solid phase on the surface of the adsorbate. Adsorption process include granular activated carbon (GAC), powder activated carbon, and synthetic absorbates with activated carbon being the most popular. Advanced oxidation processes destroy toxic organic compounds by combining ultraviolet light with ozone or hydrogen peroxide. Bioremediation uses microorganisms such as bacteria, fungi and yeast to degrade organic contaminants such as oil, gasoline, detergents, polychlorinated hydrocarbons, pesticides, and inorganic contaminates in soil and water, often rendering them harmless.[38] Chemical precipitation and ion exchange processes have been found successful in removing heavy metals from groundwater and air stripping has been selected to remove volatile gases from groundwater at many superfund sites.[20] Table 5.1 gives a summary of treatment technologies and the types of contaminants they are effective in treating.

Table 5.1 Summary of Suitability of Treatment Technologies

	Volatile Organics	Non-Volatile Organics	Inorganics	PCB/ Pesticides
Air Stripping	Suitable for most cases	Not suitable	Not suitable	Not suitable
Carbon Adsorption	Suitable for most cases	Suitable in most cases	Not a good choice	Suitable in most cases
Biological	Suitable in most cases	Suitable in most cases	Not suitable	Limited
Chemical Precipitation	Not suitable	Not suitable	Suitable in most cases	Not suitable
Advance Oxidation	Suitable in most cases	Suitable in limited cases	Not Suitable	Suitable in most cases

6. Recommended Modules

The following paragraphs present a description of technologies suggested for development as MTM prototypes for use at the Rhode Island Environmental Training Center and brief description of the technology and it's application. These modules are for above ground treatment of ground water received from collection wells. The modules do not address the location and sizing of extraction or injection well systems, but do allow for storage and treatment of water extracted from the aquifer while developing these wells.

6.1 Granular Activated Carbon Adsorption

Adsorption is a process in which matter is extracted from one phase and concentrated at the surface of another. Carbon adsorption is basically a simple process that owes it's reliability to the ability of carbon to continue functioning under wide ranges of influent contaminant concentrations. Adsorption is facilitated by the large surface area of GAC which is attributed to it's pore

structure. In certain applications, biological degradation also occurs on the granules which complements the adsorption process in removing organic material.[3] GAC can also function as a filter to remove suspended solids. The different removal mechanisms of GAC may be selectively exploited by operating the adsorbers in different configurations (series, parallel, upflow, downflow, recycle, fixed-bed, expanded bed). Therefore, GAC can be designed to serve several different functions in a treatment train (pre-filter, primary removal, polishing).

GAC is effective in removing a wide range of organic contaminants (refractory and biodegradable) found in ground water, however it does have it's limitations. Compounds that have low molecular weight and high polarity are not recommended for GAC adsorption.[10] High suspended solids (>50 mg/L) and oil and grease (<10 mg/L) may cause fouling of the carbon and required frequent backwashing.

Section 7 of this paper present a conceptual design of a MTM using GAC technology.

6.2 Prefilter

Pre-filtering may be necessary to remove suspended solids if the water contains a high concentration of suspended solids. Usually this is not the case with ground water and this step may not be necessary. Downflow GAC columns will remove the suspended solids, but will require frequent backwashing if there is a high concentration of suspended solids. A simple gravity flow, sand or dual media filter would serve to remove the suspended solids if required.

6.3 Biodegradation Reactor

While GAC adsorption and air stripping simply transfer contaminants from one phase to another, biological treatment has the potential to completely destroy the contaminant compounds. Most common chemical compounds found in fuels and oils will biodegrade naturally over a period of considerable time. Enhancing the biodegradation process can greatly speed up this process. The

variables which need to be controlled in aerobic biodegradation include temperature, pH, dissolved oxygen, rate of mixing, and nutrient concentration.

Biological treatment processes can be divided into two categories, suspended growth and fixed-film systems.[38] Suspended growth systems are the type of system typically employed in wastewater treatment which use an aeration basin containing microorganisms to metabolize organic material and clarifier basin to separate the liquid stream from the biomass. Fixed-film biological processes promote a growth of a slime layer of microorganisms on a support medium. A promising approach, called biological activated carbon (BAC) integrates biological removal and GAC adsorption into a single unit process. BAC systems consist of a biological activated, fluidized-bed reactor using GAC as the support medium for the microorganisms.[31] In general, biological process are particularly well suited for low concentrations of toxic pollutants. Microbial activity can be inhibited by factors such as high concentrations of heavy metals, the presents of toxic organic substances, inorganic salts and the formation of toxic byproducts. Ideally the biodegradation process should be designed to maximize the rate of degradation of contaminants and minimize the level of toxic substances during operation. Often biological treatment is followed by GAC adsorption for effluent polishing and to provide back-up treatment in the event of failure of the biological system.

It is recommended that two different modules be developed to study biological treatment. One module is the GAC adsorption module which is designed with an expanded-bed column which can be operated as a fixed-film biological reactor. The recommended second module is a conventional aeration basin/clarifier, suspended growth system with recycle. This module could serve multiple rolls: the aeration basin could be configured as a air stripping process and the two basin system could be configured to operate as coagulation/flocculation and settling basins for chemical precipitation of suspended solids.

6.4 Carbon Regeneration

Granular Activated Carbon treats a wide range of contaminants. But it does not destroy contaminants. The adsorption process produces spent carbon which must be disposed of or regenerated. The cost of disposing carbon saturated with hazardous materials and buying new carbon is prohibitive in most situations. Therefore, most facilities regenerate the carbon on-site, or have a contractual agreement with the carbon supplier to take away the spent carbon and replace it with carbon regenerated from a centralized, large scale regeneration facility.

Several processes exists for regeneration of carbon including thermal processes such as multiple-hearth furnace, fluidized bed, rotary kiln, and infrared; and non-thermal processes such as supercritical fluid extraction, and biological regeneration.[9,18,19,39,41]

No matter the method of regeneration, the fundamentals are basically the same. In general, substances are either reversibly or irreversibly adsorbed on activated carbon.[26] Reversibly adsorbed substances can be removed intact by application of heat or by extraction with solvents such as steam or supercritical carbon dioxide. Biological regeneration uses a microbial population to metabolize certain absorbed substances. While this process shows promise as an economical way to regenerate carbon, biological processes are inherently sensitive to environmental conditions and inhibitory contaminants. Specific contaminant/carbon/microorganism test are necessary to evaluate if biological regeneration is feasible. While literature shows this process is being studied at the pilot plant level, very little information is available concerning full scale operation using this process.

Irreversibly adsorbed substances are those which have reacted chemically with the activated carbon or other adsorbed compounds. These substances cannot be entirely removed by non-thermal processes.[39] For this reason, thermal regeneration is the most common method of recovering carbon. Prior to thermal regeneration, the carbon is dewatered using gravity draining, vacuum, or pressure filtration. The carbon is dewatered to about 50 percent dry substance. Next, the spent carbon is dried and heated to

temperatures in the range of 400 to 600 °C. Reversibly adsorbed materials are driven off and irreversibly adsorbed materials decompose and are partially desorbed, leaving behind a char residue. In the final stage of thermal regeneration, known as reactivation, the carbon is heated to temperatures in the range of 800 to 1000 °C in an atmosphere containing a high concentration of steam.[26] The residual char is gasified, and the original pore structure of the activated carbon is effectively resorted. Optimum process conditions depend on the type of carbon, application, and characteristics of the regeneration system. The negatives of thermal regeneration are the large energy costs and relatively large quantity of lost carbon (5-12%).

For small scale operations (< 3,000,000 lb/d) such as MTM's, infrared furnaces have been shown to be the most cost-effective way to regenerate the carbon compared to multihearth and fluid-bed systems.[1,31] IR furnaces offer fast heat-up and shutdown times. Since infrared (IR) furnaces use IR lamps as the heat source, only an electrical power source is required thus eliminating the need for extra petroleum products on-site and the associated possibility of spills. Furthermore, IR furnaces have been employed to incinerate contaminated soil as well as reactivate carbon. Thus, an IR incineration MTM could serve the dual functions of destroying contaminants in contaminated soil and destroying the contaminants transferred to the GAC. The economic break-even point for on-site regeneration vs. replacement of spent carbon is reported to be 2,000 lb/day.[1,4,23] Based on calculations presented in section 7, the carbon use rate for the regeneration module is only 58 lb/day, however, if the soil incineration is added, carbon regeneration may become feasible.

Figure 6.1 Infrared Incineration MTM

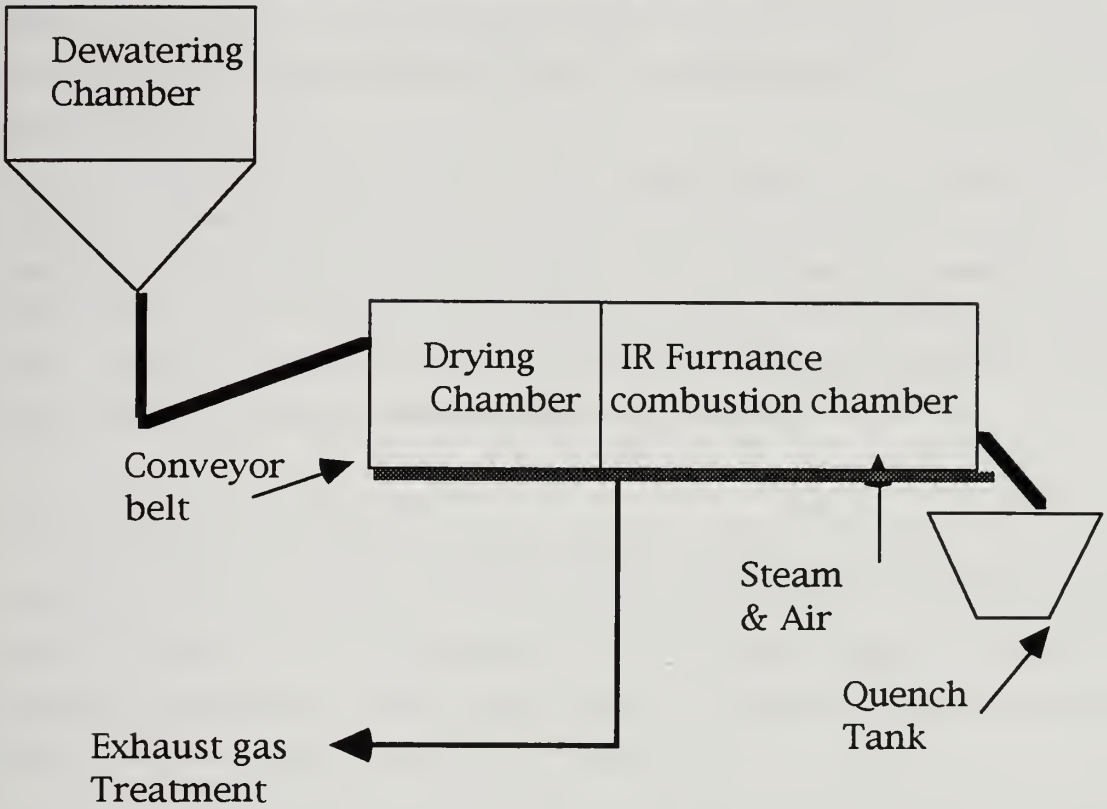


Figure 6.1 indicates the major components of an infrared furnace. The unit includes a dewatering chamber, drying chamber, combustion chamber, and belt-type conveyor.[4,43] The heat source consists of infrared lamps supported above the combustion chamber to provide a highly concentrated intense heat along the length of the chamber on the material on the conveyor belt so that maximum heat is directed to the material with minimum loss. The combustion chamber is adapted to be maintained at a slight vacuum to minimize escape of gases. Carbon or soil is fed directly into the combustion chamber onto the conveyor belt where it is leveled to a layer approximately .75 inches thick. Combustion gases are counterflowed along the chamber for preheating and drying the material. Air is passed along the infrared lamp fixtures isolated from the combustion chamber to cool the fixtures without affecting the atmosphere in the combustion chamber. Process temperatures typically range from 650 °C in the drying zone to 900 °C in the reactivation zone.[4]

The atmosphere in the combustion chamber is controlled by injection of oxidizing air or steam to control incineration. The treated material is discharged into a quench tank at the end of the conveyor belt and combustion gas is discharged at the input end of the conveyor belt.

Shirco Inc. of Dallas, Tx. manufactures IR incineration systems which can be used for soil incineration or carbon reactivation.[4,23,26] The smallest unit reported is designed to regenerate 100 lb/hour. The unit is four feet wide and twenty feet long, weighs 17,000 lb and can easily be configured on a mobile platform. The power requirement is 100 KW.

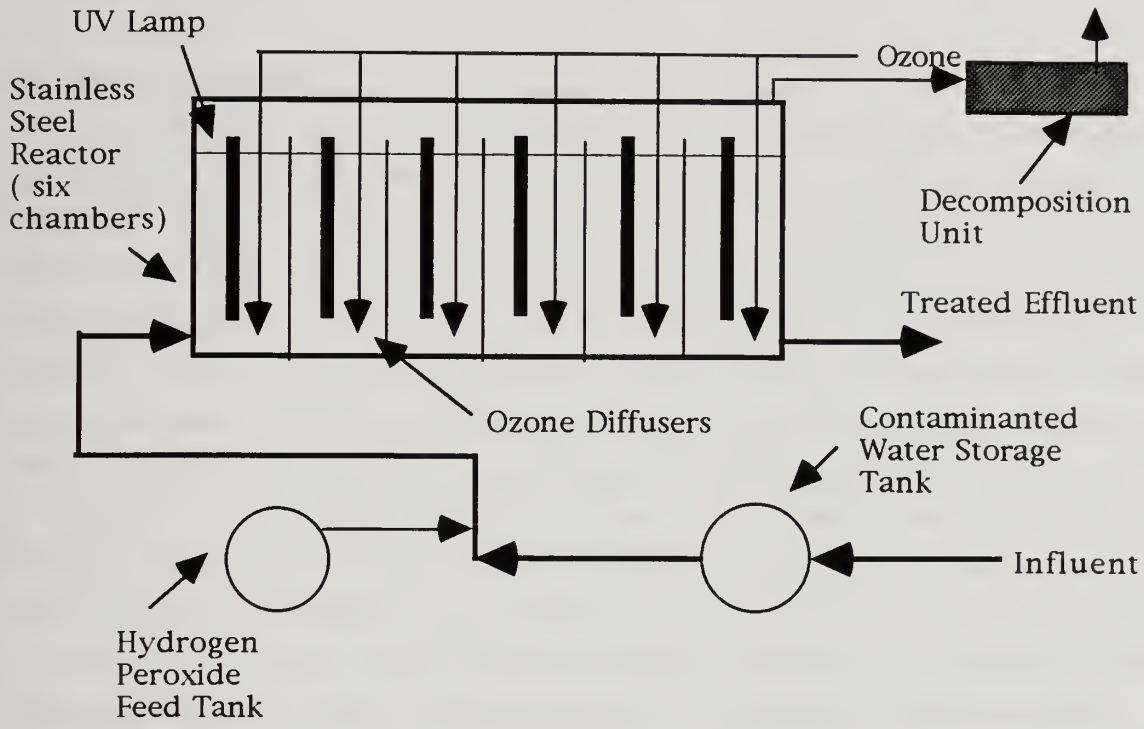
6.5 Advanced Oxidation

Advanced oxidation technologies work by combining two methods for breaking down toxic organic compounds: ultraviolet light (UV) and an oxidant, or a combination of oxidants such as ozone or hydrogen peroxide. This technology is effective in destroying VOCs, semivolatiles, and PCBs/pesticides.[21,29,40,41]

A disadvantage of advanced oxidation processes is that the technology depends on the light penetrating the water. Suspended particles, oils, or anything else that might restrict UV ray penetration need to be removed earlier in the process. Also metals in the influent may cause fouling of the lamps and reduce their intensity. A major advantage of advanced oxidation systems over carbon adsorption is that they eliminate contaminants rather than transfer them from a liquid to solid phase which must subsequently be disposed of.

Ultrox has developed an advanced oxidation system using UV radiation, ozone, and hydrogen peroxide. The major components of the system are the UV/oxidation reactor module, an air compressor/ozone generator module, a hydrogen peroxide feed system, and a catalytic ozone decomposition unit. A sketch of the system is shown in figure 6.2.

Figure 6.2 Sketch of Ultrox UV/Oxidation Treatment System [21]



The contaminated water first comes in contact with hydrogen peroxide as it flows through the influent line to the reactor. The water then comes in contact with the UV radiation and ozone as it flows through the reactor at a specified rate to achieve the required hydraulic retention time. As the ozone gas is transferred to the contaminated water, hydroxyl radicals form. The hydroxyl radical formation from ozone is catalyzed by the UV radiation and hydrogen peroxide. The hydroxyl radicals, in general, are known to react with organics more rapidly than the oxidants ozone, hydrogen peroxide, and UV radiation.[21,41] They are also much less selective in oxidation reactions than the three oxidants. Ozone that is not transferred to the contaminated water will be present in the reactor off-gas. This ozone is destroyed by the decomposition unit before being vented to the atmosphere.

Advanced oxidation offers the advantage of being more cost effective in treating poorly adsorbed compounds such as vinyl chloride. However, the major reason it is recommended as a MTM is

because it offers students a chance to investigate a new innovative technology which shows great promise in destroying many contaminates in ground water and wastewater applications.

6.6 Air Stripping

Air stripping is a mass transfer process in which a substance is transferred from the solution in water to solution in air. Compounds with a high Henry's law constant are more easily stripped from water than one with a lower constant. There are four basic configurations of equipment use for air stripping: diffused aeration, counter-current packed column, cross-flow towers, and coke tray aerators. In the counter-current configuration, water flows down through the column containing a packing material with air flow up through the column. In the cross-flow tower, water flows down through the packing as air flows across the water flow path. A coke tray aerator is basically a plate with no forced flow of air where the water trickles down through several layers of trays/plates. Diffused aeration uses basins similar to standard wastewater treatment aeration basins. Counter current packed towers are most often used in ground water treatment. The diffused aeration basin offers the advantage, that with little modification it can also serve a biological reactor.

Organic compounds can be removed from ground water by carbon adsorption or air stripping. In general air stripping is the cheapest alternative, but it is only effective in the removal of volatile organics. Carbon adsoption is effective in the removal of most organic compounds, with a few exceptions such as low molecular weight compounds like amines, nitrosamines, glycols and certain ethers.[20]

A disadvantage to air stripping is it's vulnerability to ambient air temperature. Removal of very soluble compounds may become impossible at low ambient temperatures.

The type of air stripping equipment recommended for this project is a diffused air basin which could also serve as a biological reactor or coagulation/flocculation basin.

6.7 Off-Gas Treatment

If regeneration or air stripping are used then the off-gas must be treated to remove potential air pollutants. Catalytic incineration, thermal incineration, and GAC adsorption are the most prevalent methods. GAC is generally more cost efficient for use with air stripping towers. Afterburners require large amounts of energy for high-temperature combustion of off-gas, but provide ultimate destruction of contaminants while GAC concentrates contaminants and must ultimately be disposed of, or regenerated. The afterburner oxidizes the organic compounds and the scrubber removes particulate matter and any soluble chemicals from the gas stream. Since the ultimate goal is destruction of the contaminants vice volume reduction, an infrared afterburner with a wet scrubber is recommended for treatment of off-gas. GAC adsorption to treat off-gas, just to turn around and recycle the contaminants through the regeneration/incineration module would make little sense.

Probably the most feasible design would be to incorporate the off-gas incinerator and wet scrubber as part of the regeneration/incineration module and pipe off-gas from other processes to the afterburner.

6.8 Chemical Precipitation

Chemical addition for the removal of inorganics is a well established technology. There are three common types of chemical systems which depend on the low solubility of organics at specific pH: carbonate system, hydroxide system, and sulfide system. Chemical precipitation can be either a batch or continuous flow operation. Continuous flow is most common. In this case separate tanks are required for rapid mix, flocculation, and settling.

The biological reactor, diffused air stripping, and coagulation/flocculation basins are very similar. It is recommended that consideration be given to designing a single module that could be modified to serve any of these three different processes.

6.9 Electric Generator

Separate generators could be configured to each module platform or a single large mobile generator could be brought in to power several modules simultaneously. Mounting the generators on individual modules platforms would consume valuable space, cause noise, and could be unnecessary, if power can be obtained from the local utility. Therefore, it is recommended that the generator(s) be independent of the treatment modules. Mobile generators are available in a variety of sizes and use diesel or gas fuel sources. If generators are used, fuel supply and associated storage tanks should be considered.

6.10 Water Storage

No matter what module(s) are employed, storage vessels are required to receive the ground water from the collection system and feed the water to the treatment process. Initially the tanks provide temporary storage of water from water-level drawdown tests and water used to develop wells by flushing fines from the screened area. Later, the tanks provide a surge tank for differences in pumping capacity and process flow rates while allowing the fines to settle to the bottom of the tank prior to treatment. A number of commercially available mobile storage vessels are available.

The tank's capacity should be sufficient to store a 12 hours capacity at a 20 gpm flow rate or a 24 hour pump test at 10 gpm. The tanks should be double-contained to prevent accidental spill. One suggested design is to use a 120 mil polyvinyl chloride liner and welded steel outer shell to provide structural support for the liner and secondary container.[35] A drainage mat should be installed between the liner and shell with a site glass/sensor to detect leaks. An effluent storage tank identical to the influent storage tank is also required to distribute water to the injection well system.

Volume = 10 gpm x 24 hr x (60 min/hr) = 15,000 gal.

7. Design of GAC Module

The following section presents the conceptual design of a GAC adsorption MTM and to serve as the first MTM prototype to be employed at Rhode Island Environmental Education Training Center.

7.1 Carbon Selection

One of the first steps in design of the GAC module is selection of carbon to be used. There are many different types of carbon (different sizes, different base materials, different densities,etc.). Not all carbon-solute systems behave the same. Selection of the carbon depends on the ability of a carbon to remove the contaminants of concern and to meet other system requirements such as pressure drop (head loss), carbon transport and reactivation. There are several carbons that are commercially available. In general, coal-based carbons tend to give best results during regeneration.[4] The type of carbon most suited for a given application is usually determined experimentally by creating an adsorption isotherm. An isotherm study is a laboratory simulation of a batch process in which carbon is contacted with a known concentration of solute under continuous stirring and constant temperature until the adsorption reaches equilibrium. The resulting isotherm is the relationship between the amount of substance adsorbed and it's concentration in the surrounding solution. From these measurements, values necessary to plot the empirical Freundlich isotherms can be calculated. The Freundlich Isotherm relationship is a commonly used basis for carbon capacity calculations in dilute solutions.[4,20]

Freundlich Isotherm Relationship:

$X/M = KC_f^{1/n}$

where,

$X = C_o - C_f$, the amount of compound adsorbed from a given volume of solution

M = weight of activated carbon

C_o = initial amount of compound
C_f = amount of compound remaining

K and 1/n are empirical constants characteristic of the solute-carbon system used. Graphically, K is the X/M intercept of the isotherm plot at $C_f = 1$ and 1/n is the slope of the line when the equation is plotted log-log: $\log X/M = \log K + 1/n \log C_f$. The Freundlich equation can be rearranged to calculate the carbon dose required to reduce a given initial concentration of compound to some target value by substituting $X = C_o - C_f$ into the log-log equation and solving for log M: $\log M = \log (C_o - C_f) - \log K - 1/n \log C_f$. The theoretical amount of carbon determined from the isotherm gives an indication of the efficiency of the a particular carbon-solute system.

Two common commercially available GAC particle sizes are 8 X 30 and 12 X 40. Filtrasorb 300 is a 8 X 30 carbon and Filtrasorb 400 is a 12 X 400 carbon available from Calgon. A great deal of research has been done concerning the use of both of these carbons.[1,4,15,20,34] Both demonstrate low carbon loss during transport and regeneration and both adsorb a wide range of contaminants. The EPA publication, Carbon Adsorption Isotherms For Toxic Organics, presents isotherm plots for many organic contaminants found in groundwater using Calgon carbon.[8]

Calgon Filtrasorb 400 was chosen as the carbon for this design because of it's proven track record in removing many of the contaminants of interest and, because of the availability of information concerning performance characteristics of this carbon in using the constant-pattern-homogenous-surface-diffusion-model (CPHSDM) which is used to determine empty bed contact time for the adsorbers.[1,4,14,15,16,33,34]

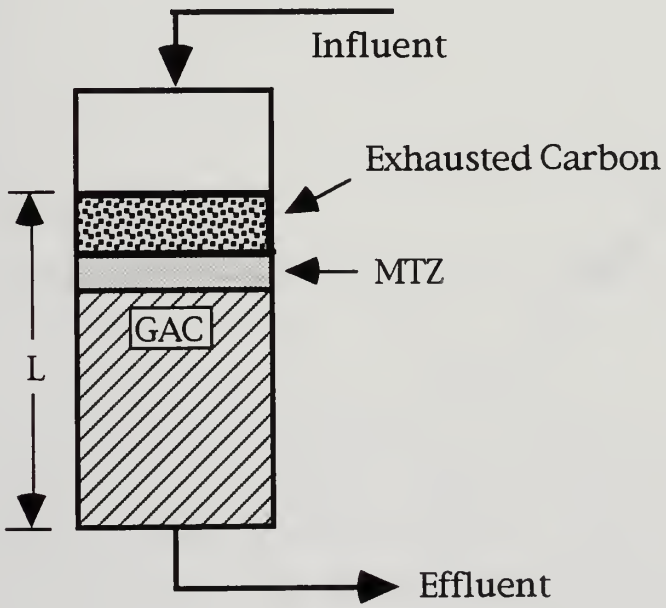
7.2 Adsorber Design Parameters

Flow rate, contact time, and carbon use must be determined before an adsorption system can be designed. The most important design parameter is contact time. Hydraulic loading, within certain ranges (2-10 gpm/ft^2) has little effect on adsorption.[34] Carbon

exhaustion or usage rate determine the amount of carbon to be replaced or regenerated. Adsorber volume depends in the carbon bed volume and how much freeboard or excess vessel capacity is required. The empty bed contact time (EBCT) is the carbon bed volume divided by the flow rate (Q) and can be interpreted as the fluid residence time in a bed which is devoid of adsorbent.

Contact time can be varied by changing the depth of the bed or by changing the flow rate. Time to breakthrough is defined as the time required to reach the point where the concentration of solute in the effluent exceeds the treatment objective. Shorter contact time result in earlier breakthrough. A plot of the impurity remaining versus the throughput volume of water treated will result in a curve called the breakthrough curve. Figure 7.1 shows how the mass transfer zone (MTZ) travels through the bed with time and Figure 7.2 illustrates a typical breakthrough curve generated from the CPHSDM for an EBCT of 17.4 minutes with a single carbon-solute system (1,2-dichloroethane and Filtrasorb 400).

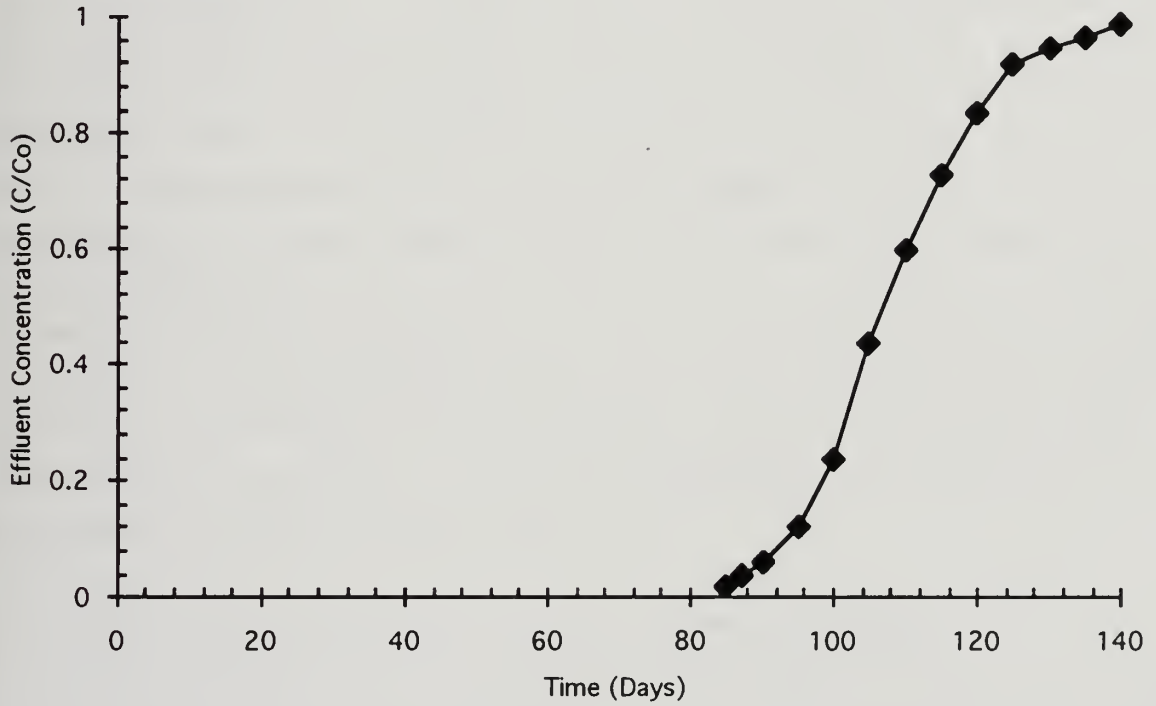
Figure 7.1 Mass Transfer Zone in Adsorption Bed



Initially the effluent has a very low concentration of solute. The solute has been absorbed by the carbon in the upper zone of the

bed. As more liquid flows through the bed, the adsorption capacity of the upper section of carbon is exhausted and the section of bed where adsorption is taking place moves downward with only a gradual increase in concentration of solute in the effluent. This wave front or mass transfer zone (MTZ) is often considered the area between 5% to 95% saturation. When the zone reaches the discharge point of the bed, the solute concentration increases rapidly approaching the influent concentration. In general the actual bed depth should be significantly greater than the MTZ to achieve a high degree of exhaustion and reduce the carbon usage rate.

Figure 7.2 Simulated Breakthrough Curve For 1,2-dichloroethane Using CPHSDM [15]



While isotherm studies can predict the relative capacity of a given carbon-solute system, they do not predict the rate of adsorption or other dynamic effects which may be present in an operating adsorber.[22,34] Breakthrough characteristics are a continuous function of effluent concentration versus total volume of water treated and depend on the characteristics of both the influent stream and the carbon bed. The two physical-chemical parameters

which determine these breakthrough characteristics are the equilibrium constant and the rate constant for adsorption. Therefore, various combinations of solutes and carbons will result in different slopes for the breakthrough curves at a given contact time. The greater the slope of the breakthrough curve the greater the rate of adsorption. Breakthrough curves can also be used to estimate the carbon use rate for a given flow rate and estimate the minimum EBCT required to maintain the adsorption wave front.

The best way to determine breakthrough characteristics and other design variables of a given solute-carbon system is to conduct pilot tests, however breakthrough curves can be described mathematically by a solution of differential equations describing adsorption. Some of these models can be used for preliminary design and cost analysis. In this case, since the system is not designed for any single solute-carbon system, but rather for a mobile operation which may encounter a variety of conditions, and thus a specific carbon-contaminant(s) system is not known, the constant-pattern-homogenous-surface-diffusion-model (CPHSDM) will be used to estimate the optimum EBCT and GAC usage rate for fixed-bed reactors. The CPHSDM model was chosen since it has successfully predicted fixed-bed adsorber dynamics in over 100 carbon-solute systems, and provides a "user-oriented solution" to the complex differential equations describing the homogeneous surface diffusion model.[15,16] The use of this model in estimating EBCT and carbon use rates is discussed in the following section.

7.3 EBCT and Carbon Use Rate Predicted By CPHSDM

The assumptions, development, and application of this model are given by Hand and Crittenden.[1,4,7,14,15,16,33] Hand and Crittenden have presented a "user-oriented solution" to the eight equation model describing the fate of an adsorbate in a fixed-bed reactor which comprise the homogeneous surface diffusion model (HSDM).[15] The equations are written in terms of dimensionless parameters which reduce the number of parameters from 10 to 5. Of the five parameters, only four act independently, since E_d is equal to the

ratio of *St* and *Bi*. The five dimensionless parameters are described below.

$$D_g = \rho_a q_e (1-\varepsilon)/\varepsilon C_o \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$Bi = k_f R(1-\varepsilon)/D_g D_s \varepsilon \phi \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$St = k_f \tau (1-\varepsilon)/R\varepsilon\phi \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

$$Ed = D_g D_s \tau/R^2 = St/Bi \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where,

q_e = adsorbent phase concentration in equilibrium with influent fluid-phase concentration (M/M)

ρ_a = Adsorbent density including pore volume (M/L^3)

ε = bed void fraction (dimensionless)

D_s = surface diffusion coefficient (L^2/t)

ϕ = sphericity, ratio of surface area of equivalent-volume sphere to actual surface area of adsorbent particle (dimensionless)

C_o = Influent fluid-phase concentration (M/L^3)

k_f = film transfer coefficient (L/t)

R = adsorbent particle radius (L)

τ = fluid residence time in packed bed, or packed bed contact time (t)

Solute Distribution Parameter (D_g) is the ratio of the mass of solute in the solid-phase to the mass of the solute in the liquid-phase under equilibrium conditions.

Biot Number (*Bi*) is the ratio of the liquid-phase mass transfer rate to the intraparticle mass transfer rate. For large Biot numbers (>30) the intraparticle-phase mass transfer rate controls the adsorption rate. Conversely, for low Biot numbers (<0.5), the liquid-phase controls the adsorption rate.

Stanton Number (*St*) and **Surface Diffusion Modules (E_d)**. For 1/n less than 1.0, the mass transfer zone will remain constant in shape as it moves through the fixed bed once it is established. Under this condition known as constant pattern, *Ed* and *St* can be viewed as measurements of bed length as compared relative to the length of the MTZ. *St* is a measure of the bed length compared to the length of the MTZ for the case in which the liquid-phase mass

transfer resistance controls the adsorption rate and *Ed* is a measure of the bed length compared to the length of the MTZ for the case in which the intraparticle-phase controls the adsorption rate.

An additional dimensionless parameter called **Mass Throughput, *T*** is defined as the ratio of mass fed as compared to the mass required to saturate the GAC. The product of (*Dg* +1) and the bed void fraction e is equal to the number of bed volumes of feed containing enough solute to saturate the adsorber.

$$T = t/\ t(Dg + 1) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where, t = real or elapsed time (t)

The following are the assumptions used by the CPHSDM:

1. The hydraulic loading and influent concentration are constant.
2. There is no radial dispersion or channeling.
3. Surface diffusion flux is much greater than pore diffusion flux as an intraparticle mass transfer mechanism.
4. The liquid phase diffusion flux can be described by the linear driving force approximation, using estimates for the film transfer coefficient k_f.
5. Adsorption equilibrium can be described by the Freundlich isotherm.
6. Plug flow within the bed.

The HSDM has been solved by both analytical and numerical solutions.[15,33] For purposes of this project, the numerical solutions for constant pattern condition ($1/n < 1.0$ and $Bi \geq 0.5$) presented by Hand and Crittenden will be used.[15] The numerical solution requires that 1/n be less than 1.0 and that the bed is long enough or has been in service long enough to establish the MTZ. As the EBCT or bed length increases, *St* increases and the MTZ spreads out and approaches constant pattern. Under constant pattern conditions, the MTZ remains constant in shape and length as it travels through the bed as indicated in figure 7.1. Therefore, curves of effluent concentration versus time (breakthrough curves) for various EBCTs are parallel. Accordingly, only minimum EBCT or *St* values required

for constant pattern need to be calculated. Curves for other EBCTs can be calculated from the wave velocity and the single constant pattern solution. As long as *Dg* is greater than 50, it's impact is negligible. Therefore, 1/n, *Bi*, and *St* are the only parameters required to solve the Constant Pattern HSDM and only 1/n and *Bi* need to be varied to generate solutions to the CPHSDM.[15]

The equations for minimum Stanton numbers, St_m (required for constant pattern condition), associated with each solution for a given *Bi* and 1/n are presented in Appendix B. The following empirical equation for throughput (T) as a function of St_m, *Bi*, and 1/n has been fitted to constant pattern solutions.

$$T(Bi, 1/n, St_m) = A_o + A_1(C/C_o)^{A_2} + A_3/(1.01-(C/C_o)^{A_4}) \quad \ldots(6)$$

where, C/C_o = effluent concentration divided by influent concentration (dimensionless)

The constants in this equation can be found in Appendix C. Shorter EBCTs (or lower *St* values) than the solutions found in Appendix C can be used if a 10 % error in the predicted breakthrough time for a given C/C_o value can be tolerated. The solutions presented in Appendix C are given in terms of reduced concentration and mass throughput. To convert mass throughput into time, St_m can be calculated using the equations of Appendix B and minimum empty bed contact time required for constant pattern ($EBCT_m$) can be calculated from the following equation.

$$EBCT_m = \tau_m/\varepsilon = St_m \, R\phi \, / \, k_f(1-\varepsilon) \quad \ldots\ldots\ldots \quad (7)$$

Where, τ_m is the minimum packed bed contact time required to establish constant pattern (t).

Now the mass throughput can be converted to elapsed time by the following equation.

$$t_m = \tau_m(Dg + 1)T \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

Where, t_m is the elapsed time corresponding to minimum EBCT required to establish constant pattern conditions (t).

The steps presented by Hand and Crittenden[15] to find solutions using the CPHSDM are:

1. Obtain the Freundlich parameters K and 1/n from isotherm studies; the surface diffusivity D_S from batch rate tests; calculate or determine the liquid-phase mass transfer coefficient K_f .

2. Calculate *Dg* and *Bi* from equations 1 and 2 respectively.

3. Obtain appropriate constants from Appendix C for given 1/n and Bi and calculate T using equation 6.

4. Determine appropriate St_m from Appendix B and calculate $EBCT_m$ from equation 7.

5. Convert the constant pattern mass throughput to elapsed time using equation 8. This solution corresponds to an adsorber with an $EBCT_m$.

The maximum contaminant level (MCL), effluent concentration, EBCT's, and GAC use rate predicted by the CPHSDM for given influent concentrations of compounds typically found in contaminated ground water are presented in Table 7.1. An example of the procedure is presented in Appendix D.

Table 7.1 Estimates of GAC use in controlling common groundwater contaminants [1]

Compound	Influent Concentration	Effluent Concentration	EBCT (min)	GAC Use Rate (lb/1000 gal)
Dibromochloro-propane	20	.2	10	.0347
1,1,2 Trichloroethane	20	.2	10	.0347
Ethylene dibromide	10	.05	15	.0784
1,2-Dichloroethane	100	.05	20	.8611
p-Dichlorobenzene	500	75.0	10	.0204
1,2-Dichloropropane	100	5.0	15	.3912
Dichloromethane	100	5.0	40	5.1346
Chlorobenzene	100	5.0	10	0.0402
Benzene	100	5.0	15	0.1085
cis-1,2-Dichloroethylene	200	70.0	15	.6726
trans-1,2-Dichloroethylene	200	70.0	15	.4123
M-Xylene	100	5.0	10	.0122
Trichloroethylene	100	5.0	10	.1711
Tolene	100	5.0	10	.1166
Ethylbenzene	1000	50.0	10	.1157
1,1,1-Trichloroethane	500	200.0	15	.6686
Carbon tetrachloride	100	5.0	15	.2517
Tetrachloroethylene	100	5.0	10	.0760
1,1-Dichloroethylene	100	5.0	15	.2485
Vinyl chloride	100	1.0	30	2.9422

From Table 7.1, it can be seen that EBCTs required for constant pattern condition range from 40 minutes for dichloromethane to 10 minutes for tetrachloroethane and several other compounds .

It should be noted that the CPHSDM approach involves a single-solute system, not a multi-contaminant system normally found in ground water. A poorly adsorbed organic compound in the presence of a more strongly adsorbed organic may exhibit higher use rates as a result of competitive adsorption and displacement. Also, the model does not account for possible reduction of GAC's capacity or kinetics as a result of background organic matter being adsorbed on the carbon. However, these factor which reduce bed life may be offset by increases in bed life due to biological activity in the bed which, also is not accounted for in the model. [1,14,15]

An EBCT of 20 minutes was selected for this design, a value which ensures constant pattern development for all investigated compounds except vinyl chloride (30 min) and dichloromethane (40 min). Series operation of the two adsorbers will extend the EBCT to 40 minutes satisfying the constant pattern condition for even these poorly adsorbed compounds.

7.4 Adsorber Configuration

GAC Adsorbers may be arranged and operated in various configurations to obtain the most efficient use of the carbon in a given application.[4,34] The two basic modes of operation for GAC adsorbers are fixed bed and moving bed. In a fixed bed adsorber, the carbon remains stationary and the flow can be upwards or downwards. In moving bed adsorbers the water flows upwards and the carbon moves downwards under the influence of gravity. An expanded moving bed adsorber operates at a flow rate high enough to cause the carbon bed to expand, about 10%. Adsorbers can be combined in series or parallel operation depending on the application.

Adsorbers in series usually result in high, stable effluent quality since the total bed depth is increased. Parallel filters minimize head loss and can treat larger flow volumes. Upflow beds have an advantage over downflow beds in the efficiency of carbon use because they can more closely approach countercurrent contact

operation by discharging spent carbon from the bottom while adding fresh carbon at the surface while the bed is in operation. Countercurrent operation result in the minimum use of carbon. Downflow operation results in the best filtration of suspended solids and adsorption of impurities, but require backwashing to dislodge and remove suspended solids accumulated at the surface of the bed. Expanded bed absorbers can treat water with higher suspended solids with lower head loss and promote the growth of a biological film which has been reported to improve contaminate reduction.[2,19,38,42] However, since expanded beds do not filter suspended solids, downstream filtration is required. Adsorbers may be open or closed to atmospheric pressure.

This prototype uses two closed fixed-bed, downflow adsorbers in series and an expanded bed adsorber which may be modified to operate as a BAC reactor. From the process reliability standpoint, each of the downflow adsorbers has an EBCT of 20 minutes which will remove most contaminants to target levels, thus providing adequate treatment even with one contactor taken off-line for maintenance or repairs.

This flexible design allows students to investigate the effectiveness of various modes of operation in contaminant removal and allows for the operation of the module to be tailored to a specific field situation. For example, the following modes of operation can be studied with this module:

1. Two downflow adsorbers in series.
2. An expanded bed adsorber in series with a downflow adsorber.
3. An expanded bed, fixed-film biological reactor with a recycle adsorber loop followed by a conventional downflow adsorber.

The design of the downflow carbon columns is based on fixed-bed downflow operation with capacity for 50 % expansion during backwash. The expanded bed column is designed to operate at 10% expansion with pulsed carbon removal on a weekly (135 lb) basis. A recycle loop is included for future modification of the expanded bed adsorber to serve as a BAC reactor.

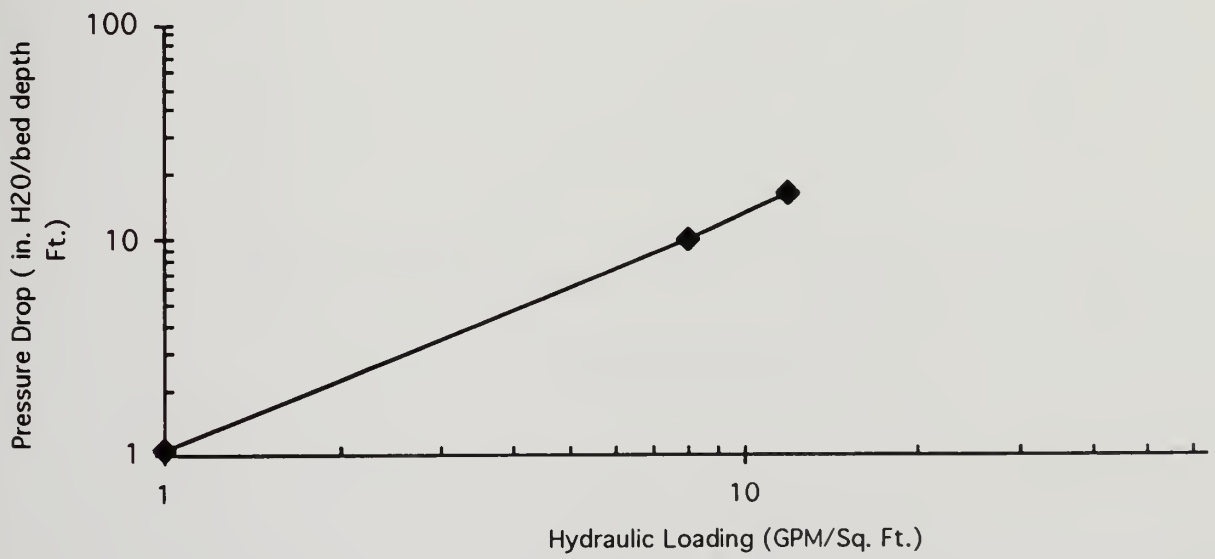
7.5 Other Design Considerations

Several other items need to be considered during design: 1. Head loss versus hydraulic loading rate; 2. Backwash flow rate; 3. Underdrain system; 4. Operating Pressure and air/vacuum releases; 4. Accommodations to transport carbon to and from the vessel; 5. Construction materials; and 6. Special features required if the vessel is to operated as a biological reactor.

7.5.1 Head Loss Vs. Hydraulic Loading Rate

Although the best way to determine hydraulic head loss and required flow rate for expansion is by pilot testing, for this design Figures 7.3 and 7.4 will be used which relate head loss and % expansion to hydraulic loading.[4,34] Hydraulic head loss is directly related to flow rate and inversely related to particle size. In this design, a hydraulic loading rate of 4 gpm/SF is selected for the fixed bed operation. For a hydraulic loading rate of 4 gpm/SF, the corresponding head loss is 6.16 inches per Ft. of bed length = 5.65 Ft. head loss through an 11 Ft. carbon bed.

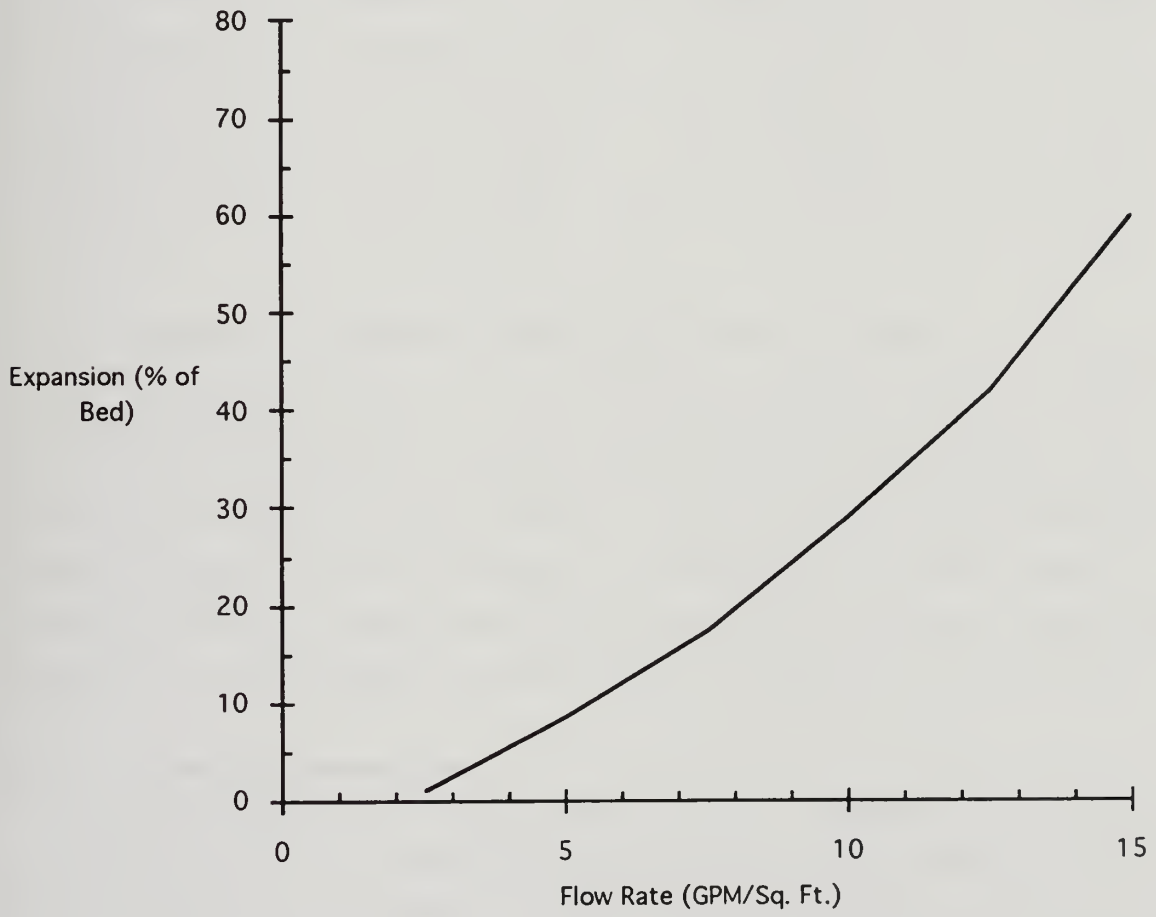
Figure 7.3 Pressure Drop VS. Hydraulic Loading For Filtrasorb 400 [4,34]



7.5.2 Backwash Flow Rate

It has been found that at about 10 % expansion, suspended solids will pass through a bed, and backwashing of a downflow adsorber requires 10-50 % expansion.[34] The corresponding flow rates from Figure 7.4 for 10 and 50 % expansion are 6 and 12 gpm/SF respectively.

Figure 7.4 Expansion of Filtrasorb 400 Carbon Bed At Various Flow Rates [34]



7.5.3 Underdrain System

If properly designed, the adsorber should not only provide adequate contact time between the carbon and water, but also facilitate carbon withdrawal and replacement, and the separation of carbon and water at the inlet and outlet of the adsorber. A 45 degree cone at the top and bottom of the vessel aids in carbon distribution and removal. The cone at the bottom prevents carbon from remaining in the corners during withdrawal and the cone on the top ensures uniform distribution of fresh carbon, especially in the case of an upflow reactor. A cone shaped underdrain plate with 316L stainless steel screened nozzles (.02 inch openings) is provided at the top and bottom to remove/distribute the flow while blocking carbon from escaping the vessel. The expanded bed and fixed bed adsorber vessels are virtually identical except for physical dimensions. (See Drawings A-1 and A-2, Appendix F)

7.5.4 Operating Pressure And Air/Vacuum Releases

Since the carbon is contained in closed vessels sealed from atmospheric pressure, air must be released when filling the vessels and the vacuum must be broken when draining the vessels to prevent structural damage to the vessel. The location of a typical air-vacuum release valve is shown in Drawing A-1 of Appendix F. The maximum internal operating pressure is calculated to be 16 psi, Appendix A. (Recommend design vessel to ASME, 30 psig code)

7.5.5 Carbon Transport

Spent carbon is discharged from the adsorbers as a slurry and usually travels to a spent carbon storage tank rather than directly to a reactivation system. After reactivation the carbon returns to the adsorbers as a slurry. Carbon vendors usually ship carbon in bulk slurry vessels such as truck or rail car, or for smaller systems, by bag or drum.

Transfer of the carbon slurry (typically 1-3 lb carbon/gal) can be accomplished by gravity, water-jet eductors, centrifugal

pump, or blowcases.[4,34] In this case, since the quantity of carbon to be transported is small, the carbon will be removed from the vessels by gravity discharge and returned to the vessel by a rubber impeller centrifugal pump. The expanded bed adsorber will operated as a pulsed bed adsorber with spent carbon replaced on a weekly basis.

7.5.6 Construction Materials

Materials for construction of GAC systems vary. For contaminated groundwater applications, epoxy-coated steel or fiberglass is used for the vessel and plastic or fiberglass is used for piping.[4] The suggested materials for this design are: PVC piping for influent and effluent streams; 316L SS for carbon transport piping and nozzle screens; fiberglass for the center section of the GAC vessels; and carbon steel for the influent and effluent end sections with the entire interior surface coated with epoxy (40 mils - Wisconsin Plasite 4020).[4] Rectangular and square structural steel tubing are used for the skids and support frame. (See Drawings S-1 through S-6, Appendix F)

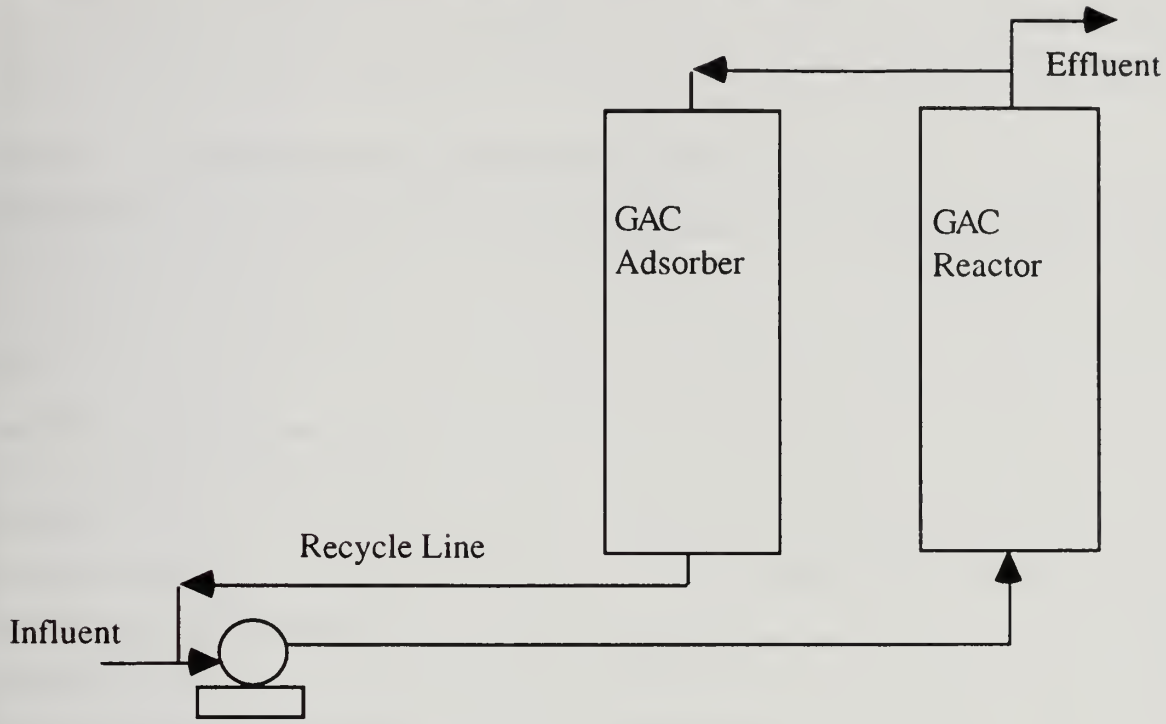
7.5.7 Special Features --- Biological Reactor

Several studies have been conducted which demonstrate that the efficiency of GAC can be increased by promoting the growth of biological film on GAC and thus create a type of fixed-film biological reactor.[11,19,37,42] As the activated carbon adsorbs organics from the water, it creates a substrate for biological growth. To promote and control the biological process several things need to be controlled such as pH, nutrients, oxygen supply, recycle ratio, and temperature. BAC reactors are operated in the expanded bed mode. Benefits which can be realized by promoting biological growth include extension of the carbon adsorption service life, as the microorganisms clean adsorption sites, and removal of non-adsorbing materials due to the biological activity. A major concern is the vulnerability of microorganism to inhibitory compounds.

The GAC expanded-bed reactor is capable of treating wastewater containing inhibitory compounds with combined biological and physical removal mechanisms.[11] GAC adsorption maintains the concentration of inhibitory compounds at low levels permitting the acclimation and subsequent metabolism of biodegradable inhibitory materials. Continuous treatment of waste waters containing inhibitory concentrations of refractory compounds has been found possible by continuously removing and replacing GAC in expanded-bed reactors, however the replacement of GAC is expensive and biomass attached to the removed GAC is lost which reduce the age of the biomass in the reactor and thus reduces the efficiency of biological removal. Long biomass age enhances the removal of easily biodegradable compounds and is essential in the biodegradation of inhibitory substrates. Fox and Suidan have investigated the use of a hybrid GAC reactor consisting of a GAC expanded-bed reactor with a supplemental GAC adsorber in the recycle line to treat refractory and inhibitive compounds.[11] This process separates the biological and physical removal processes, thus overcoming the disadvantage of reduced biological activity due to carbon replacement. The use of this process has only been studied in the laboratory, however it shows great promise. Therefore, this design includes a recycle line to allow the system to operate similar to the experimental apparatus of Fox and Suidan (See Figure 7.5).

An influent heating chamber, oxygen generator, and storage tanks for nutrient addition and chemical control of pH could easily be added to the expanded bed system.

Figure 7.5 Hybrid GAC Reactor Flow Diagram



7.6 Recommended Adsorber Design Values

Tables 7.2 and 7.3 summarize the values selected for the design parameters of the down flow and expanded-bed adsorbers respectively.

Table 7.2 Downflow GAC Adsorber Design Data

Parameter	Value
Flow Rate	20 gpm
Hydraulic loading	4 gpm/sq. ft
EBCT	20 min
Column diameter	2.5 ft (30 in.)
Column side wall depth	16.5 ft
Carbon type	Calgon, Filtrasorb 400
Carbon size	12 X 40 mesh (90% passing)
Depth of Carbon bed	11 ft
Carbon Mass	1658 lb
Estimated Service Life	63 days

Calculations:

Vessel area = 20 gpm/4 gpm/ft^2 = 5.0 sq. ft

Vessel Diameter = ((4 X Area)/π) $^{1/2}$ = 2.53 ft (30 inches)

Depth of carbon bed = 4 gpm/ft^2 X 20 min. X ft^3 /7.48 gal. = 11 ft.

Carbon volume = 11 ft X 5.0 sq. ft = 55.0 ft^3

Carbon mass = 55 ft^3 X 30.14 lb/ft^3 = 1658 lb

Column sidewall depth for 50% expansion during backwash = 1.5 X 11 ft = 16.5 ft

Service life based on 500 ug/L of 1,1,1-Trichloroethane: Service life = 63 days

Carbon use = .6686 lb/1000 gal X 20 gal/min(1440) = 19.3 lb/day

Table 7.3 Expanded-Bed Adsorber Design Data

Parameter	Value
Flow Rate	20 gpm
Hydraulic loading	6 gpm/sq. ft
EBCT	20 min
Column diameter	2 ft (24 in.)
Column side wall depth	16 ft
Carbon type	Calgon, Filtrasorb 400
Carbon size	12 X 40 mesh
Depth of Carbon bed	16 ft
Carbon Mass	1447 lb
Carbon Use	19.3 lb/day

Calculations:

Vessel area = 20 gpm/6 gpm/sq. ft = 3.3 sq. ft

Vessel Diameter = $((4 \times \text{Area})/\pi)^{1/2}$ = 2.06 ft (24 inches)

Depth of carbon bed = 6 gpm/ft^3 X 20 min. X ft^3 /7.48 gal. = 16 ft.

Carbon volume = (16/1.1) ft X 3.3 sq. ft = 48 ft^3

Carbon mass = 48 X 30.14 lb/ft^3 = 1447 lb

Column sidewall depth equals bed depth = 16 ft

Carbon use based on 500 ug/L of 1,1,1-Trichloroethane using fixed-bed usage rate:

Carbon use = .6686 lb/1000 gal X 20 gal/min(1440) = 19.3 lb/day

7.7 Pipes, Valves, and Pumps

Worksheets for selection of pipes size and pump characteristics are contained in Appendix E. Drawings M-1, M-2 and M-3, Appendix F, are diagrams of the flow layout with the location of pumps, valves and pipes. All of the valves in the influent, effluent, and backwash lines are Ball Type On/Off valves except u and b, which are gate valves, and z, d, f, i, and j which are combination check valve/shut off valves. Carbon transport valves and pipe materials will be discussed separately.

There are five independent piping systems: 1. The system from the influent storage tank through the fixed bed GAC adsorbers to the discharge booster pump; 2. The system from the booster pump to the effluent storage tank; 3. The system from the influent storage tank through the expanded bed and fixed bed GAC adsorbers to the discharge booster pump; 4. The system which delivers the carbon slurry from a storage tank to the adsorbers; 5. The backwash system; and 6. The gravity drain system for removing carbon from the adsorbers. The following tables summarize the recommended pump characteristics. Worksheets for the calculation of the pump/system characteristics are presented in Appendix E.

1. The system from the influent storage tank through the fixed bed GAC adsorbers to the discharge booster pump.

Table 7.4 Pump/System Operating Point Specifications (P5 & P6)

TDH (Ft.)	23.9
Capacity (GPM)	20
Pipe Inside Diameter (inches)	1.5
Velocity (fps)	3.63
Whp	.12
Bhp @55% efficiency	2/10
NPSH available (Ft.)	32.5

2. The system from the booster pump to the effluent storage tank.

Table 7.5 Pump/System Operating Point Specifications (P2)

TDH (Ft.)	9.5
Capacity (GPM)	20
Pipe Inside Diameter (inches)	1.5
Velocity (fps)	3.63
Whp	.05
Bhp @55% efficiency	1/10
NPSH available (Ft.)	42

3. The system from the influent storage tank through the expanded bed and fixed bed GAC adsorbers to the discharge booster pump.

Table 7.6 Expanded Bed Pump/System Operating Point Specifications (P4)

TDH (Ft.)	39
Capacity (GPM)	20
Pipe Inside Diameter (inches)	1.5
Velocity (fps)	3.63
Whp	.2
Bhp @55% efficiency	1/3
NPSH available (Ft.)	33

4. Two inch SS pipe is used for the system which delivers the carbon slurry from a storage tank to the adsorbers. Velocity should be at least 3 fps to prevent carbon from settling, but not greater than 10 fps to prevent carbon abrasion and pipe erosion. The EPA Process Design Manual For GAC presents a diagram to calculate pressure loss per 100 ft of 2 inch pipe for various lb carbon/gal.[34] This diagram was used for worksheets in Appendix E. Long radius elbows should be used to reduce abrasion of the pipe and damage to the carbon. Because of the abrasive nature of a carbon slurry, valves used in slurry lines must not be used for throttling service or flow control, this can be accomplished with the water supply line. Valves in carbon slurry lines are for shut or check service only. The valves should offer no restriction to slurry transport when in the open position. Globe and gate valve are not suited for this service since they will not properly seat due to obstruction and abrasion caused by carbon particles. Diaphragm valves offer limited restriction, but have a flexible element which will be worn by abrasion over time and require replacement. Wafer stock valves or knife gate valves seem to be the best choice for shutting off flow and swing check valves designed to operate in a vertical line seem to be the best choice for backflow prevention.

5. The backwash system.

Table 7.7 Carbon Supply Pump/System Operating Point Specifications (P3)

TDH (Ft.)	40
Capacity (GPM)	40
Pipe Inside Diameter (inches)	2.0
Velocity (fps)	4.07
Whp	.33
Bhp @55% efficiency	1/2
NPSH available (Ft.)	27

Table 7.8 Backwash Pump/System Operating Point Specifications (P1)

TDH (Ft.)	44
Capacity (GPM)	60
Pipe Inside Diameter (inches)	2.5
Velocity (fps)	3.93
Whp	.7
Bhp @55% efficiency	1 - 2/10
NPSH available (Ft.)	33

6. A simple gravity drain system is employed to remove carbon from the adsorbers using 2 inch SS pipe.

7.8 Description of Operation

The system is composed of three separate assemblies: the adsorber section, the auxiliary equipment section, and the upper catwalk. See drawings S-1 through S-6 in Appendix F. All of these assemblies have allowable weights, heights, lengths, and widths to be transported on standard lowboy trailers. After the assemblies arrive they must be attached together. A small crane or other

lifting device will be required to move the assemblies into place. All pipe connections are flanged for easy connection.

Once the assemblies are properly attached together and the system is pressure tested, the system is ready to be put into operation. The system is designed to be operated in several modes. Valve settings and a brief description of the following operations are given. Drawings M-1, M-2, and M-3 of Appendix F illustrate the flow layout and location of valves and pumps.

7.8.1 Operations

1. Two downflow adsorbers in series.
2. An expanded bed adsorber in series with a downflow adsorber.
3. An expanded bed, fixed-film biological reactor with a recycle adsorber loop followed by a conventional downflow adsorber.
4. Carbon import/export for fixed bed adsorber.
5. Carbon import/export for expanded bed adsorber.
6. Backwash of fixed bed adsorber.

7.8.2 Description

1. Two downflow adsorbers in series: Operation of the two fixed bed adsorbers in series with the expanded bed off-line may be accomplished as follows: All pumps are assumed to be off. For simplicity only the case of GAC 3 following GAC 2 will be discussed. Open valves v, m, am, f, g, n, av, ag, p, i, h, o, s, aw, y, and aa. All other valves are closed. Turn on pumps P5, P6, and P2. Note, if there is less than 10 ft. head required to fill the effluent storage tank, the booster pump may not be required and can be by-passed by closing valves y and aa and opening valve ab.

2. An expanded bed adsorber in series with a downflow adsorber: The module may be operated with either fixed bed GAC following the expanded bed GAC (EBCT = 20 min.), or the expanded bed GAC followed by both fixed bed adsorbers for a total EBCT of 60 minutes. For simplicity only the operation of GAC 1 followed by GAC 2 will

described. GAC 1 followed by GAC 3 is identical except for respective valve and pump setting.

All pumps are assumed to be off; and valves am, t, k, d, a, b, g, n, r, aw, y, and aa are on; and all other valves are off. Turn on pumps P4 and P2. Pump 4 is designed to pump influent from a storage tank up through the expanded bed adsorber, down through a fixed bed adsorber to booster pump P2. Note, if there is less than 10 ft. head required to fill the effluent storage tank, the booster pump may not be required and can be by-passed by closing valves y and aa and opening valve ab.

3. An expanded bed, fixed-film biological reactor with a recycle adsorber loop followed by a conventional downflow adsorber: For recycle, gate valves u and b should be set for the desired amount of recycle of effluent from the expanded bed reactor to be sent to the fixed bed adsorber and subsequently blended with the influent stream to pump 4 from the storage vessel. All other settings are the same as series operation, fixed bed following expanded bed, except az and ax are open and aw is closed. The influent heating basin and nutrient addition tank will need to be to connected to the influent lines, and the oxygen generation unit should be piped to the GAC reactor vessel.

4. Carbon import/export for fixed bed adsorber: To remove spent carbon for regeneration, the column is taken off-line and the bed is expanded by 20-35 % by backwashing. The carbon slurry is then gravity drained from the adsorber into the storage chamber. Open valve as for GAC 2 or valve at for GAC 3. Any remaining carbon can be rinsed from the bottom of the adsorber using the backwash nozzles.

To replace carbon use pump P3 to pump carbon from a storage/slurry chamber or truck. Open valves q, j, and ad or ae for GAC 2 and 3 respectively.

5. Carbon import/export for expanded bed adsorber: The expanded bed adsorber is designed as a pulsed bed adsorber (carbon removal on

weekly basis). The carbon is removed by gravity flow from the bottom of the vessel, open valve ar. Spent carbon can be received in a storage vessel or transported by carbon slurry to dewatering chamber of regeneration unit. Carbon is replaced by a slurry flow through Pump P3 from a carbon storage vessel. Open valves j, q and ac.

6. Backwash of fixed bed adsorbers: Backwashing is required to dislodge and remove accumulated suspended solids from the top of the carbon bed which result in an increased pressure drop across the bed. The frequency of backwashing depends in the suspended solids concentration of the influent. Only the fixed bed columns should required backwashing since the expanded bed adsorber allows suspended solids to pass through the bed. When backwashing the carbon, it is important to expand the carbon bed slowly, without incurring a carbon loss and to allow the bed to settle in a stratified state so that the adsorption wave front will be maintained and the carbon use is optimized.[31]

To backwash GAC 2, set valves and pumps for series operation (GAC 1 followed by GAC 3; GAC off-line). Open valves ak, x, z, af, aq, an, ai, aj and an. Close valves ag, g, and ap. Turn on pump P1. To backwash GAC 3, set valves and pumps for series operation (GAC 1 followed by GAC 2; GAC 3 off-line). Open valves ak, x, z, af, ag, ai, aj, ap and an. Close valves ah, aq, and i. Turn on pump P1.

Backwash water can come from the effluent tank or an alternative clean water supply. Backwash waste water should be returned to the influent supply tank for subsequent treatment.

7.9 Electrical System

Drawing E-1 of Appendix F is a sketch of the electrical system used to estimate cost. NEMA 3R (rainproof and sleet resistant) enclosures, weatherproof receptacles, lighting, and pump on/off switches are recommended. All copper THNN wiring. Conduits and boxes are all oversized to allow additional wires to be pulled if desired for additional sensors/controls. Two circuits are provided

the pumps, one for lighting, two for receptacles, two for BAC additions, and three spares. (Total 10 circuits). The circuit panel, flow recorders, and pressure recorders are located in the large NEMA 3R equipment enclosure. The enclosure is oversized to allow future expansion and an additional enclosure is provided for addition of digital data acquisition equipment if desired.

Table 7.9 Summary of Circuits

Circuit	Power (watts)	Amps	Breaker (Amps)	Wire (gage)
Lighting	600	6	15	14
Receptacles	demand	20	20	12
Receptacles	demand	20	20	12
Pump 1 & 2	840	8.2	15	14
Pump 3,4, 5, & 6	796	8.0	15	14
BAC Expansion			15	
BAC expansion			15	
Spare			15	
Spare			20	
Spare			20	

Calculations:
Single phase pump motors @ 120 Volt AC.
one horsepower = 647 watts
Amperes = Watts/(Volts X Power factor)
Power Factor approximately .85 for small motor
Pumps sizes listed in Appendix E.

7.10 Structural

The framework of the skid and attached structural members are shown in drawings S-1 through S-6 of Appendix F. The structural frame is made of welded rectangular and square steel tubing; gratings are aluminum; auxiliary section roof is 1/4 inch aluminum textured sheet metal; guardrails are pre-assembled 2-rail, aluminum

piping w/toe plate; and all assembly connections are made by steel bolt and hex nut. The frame is coated with high quality, rust resistant primer and enamel paint.

7.11 Monitoring and Controls

The system is designed for manual control by use of on/off valves and switches. The only automatic operation is the auto-shut-off/on of the pumps via float switches located in the influent and effluent storage tanks and auto pump shut off in the event the line pressure exceeds normal operating values (Cole-Parmer H-68020-10).[5] The recommend basic monitoring equipment include the following:

Flowmeters: Each pump and the output of valve u should be equipped with a flowmeter capable of measuring instantaneous and cumulative flow(except the carbon supply pump). These meters can provide digital output for automatic data acquisition.

Pressure Recorders: Each vessel should be equipped with pressure sensor (Cole-Parmer H-68921-02) and recorders (Cole-Parmer H-07350-64) to record maximum and instantaneous pressure. These meters can also provide digital output for automatic data acquisition. The pressure recorders can also provide a signal for auto pump shut down.

Sampling ports: Sampling ports should be placed at 1 ft. intervals along the length of the fiberglass portion of the adsorber column so that the progression of the MTZ can be studied. Also, sampling ports should be provided in the effluent and influent lines of each adsorber.

Other monitoring/control equipment which may be desired in the future include: A microprocessor based data acquisition center; Nutrient feed control, temperature control, pH control, and oxygen regulation should the BAC alternative be implemented; and A radio controlled link to a central location to indicate status and provide an alarm in the event a pump kicks off-line or some other system failure.

7.12 Cost and Weight Estimates

Worksheets for the cost estimate are contained in Appendix G. The total estimated cost is $71,900. The material and labor cost for most of the items came from Means Cost Estimating Guides. Sensor and recorder costs came from Cole-Palmer. The cost of the adsorbers themselves were difficult to estimate. Costs for similar vessels were used with a liberal markup for special manufacture. This cost is for the system itself and does not include any laboratory test equipment associated with sampling, or computer equipment for automated data acquisition. The total estimated weight is 18,095 lb, well below the 50,000 lb trailer capacity.

7.12 Cost and Weight Estimates

Worksheets for the cost estimate are contained in Appendix G. The total estimated cost is $71,900. The material and labor cost for most of the items came from Means Cost Estimating Guides. Sensor and recorder costs came from Cole-Palmer. The cost of the adsorbers themselves were difficult to estimate. Costs for similar vessels were used with a liberal markup for special manufacture. This cost is for the system itself and does not include any laboratory test equipment associated with sampling, or computer equipment for automated data acquisition. The total estimated weight is 18,095 lb, well below the 50,000 lb trailer capacity.

8. Summary and Recommendations

The concept of mobile treatment modules, recommended modules for development, and conceptual design of a GAC module have been presented for ground water treatment. Ground water treatment is only a part of total site remediation. In most cases, to fully address site remediation, a synergistic approach to treat all four contamination phases is necessary. Many of the technologies (vapor extraction, bioremediation, venting, etc.) used to remove contaminants from these other phases can also be made mobile. Development and evaluation of mobile units to remove contaminants from the soil, and vadose region would be a good candidates for future projects for the Rhode Island Environmental Education/Training Center.

Commercial manufactures offer a large range of mobile units (incineration, GAC, UV/Ultraviolet/Ozone, air stripping).[13] Many are eager to demonstrate the capabilities of their products. Agreements between these vendors and URI to use the Rhode Island Environmental Education/Training Center as a testing ground for their products may prove beneficial to all parties (business, government,students,faculty).

References

1. Adams Q.J. and Clark, R.M., "Evaluating the Costs of Packed-Tower Aeration and GAC for Controlling Selected Organics", Journal American Water Works Association, January 1991, pp. 49-57.

2. Avallone, E.A. and Baumeister, T., Mark's Standard Handbook for Mechanical Engineers, 9th Ed., McGraw Hill, New York, 1978.

3. Brown R.A. and Sullivan K., "Integrating Technologies Enhances Remediation", Pollution Engineering, May 1991, pp 62-68.

4. Clark, R.M., and B.W. Lykins, Granular Activated Carbon: Design, Operation, and Cost, Lewis Publishers, Chelsea Michigan, 1989.

5. Cole-Parmer Instrument Company Catalog, Niles, Il. 1995-1996.

6. Crittenden, J.C., and Weber, Jr. M., "Predictive Model For Design of Fixed-Bed Adsorbers: Parameter Estimation and Model Development", Journal of Environmental Engineering, ASCE, Vol. 104, No. EE2, April 1978, pp. 185-197.

7. Crittenden, J.C., and Weber, Jr. M., "Predictive Model For Design of Fixed-Bed Adsorbers: Single-Component Model Verification", Journal of Environmental Engineering, ASCE, Vol. 104, No. EE3, June 1978, pp. 433-443.

8. Dobbs, R.A. and J.M. Cohen, Carbon Adsorption Isotherms for Toxic Organics, EPA-600/8-80-023, 1980.

9. Eckart, C.A., Leman G.W., Tomasko D.L. and Hay J.K., "Pilot Scale Study and Design of a Granular Activated Carbon Regeneration Process Using Supercritical Fluids", Environmental Progress, August 1993, pp. 208-217.

10. Engineering Bulletin, Granular Activated Carbon Treatment, EPA/540/2-91/024, Cincinnati, Ohio, October 1991.

11. Fox, P., and Suidan, M.T., "A Comparison of Expanded-Bed Reactor Designs for the Treatment of Refractory/Inhibitory Wastewaters", Water Resources, Vol. 27, No. 5, 1993, pp 769-776.

12. Goodrich, J.A., Lykins, B.W., Clark, R.M., and Oppelt T.E., "Is Remediated Groundwater Meeting SDWA Requirements?", Journal of American Water Works Association, March, 1991, pp. 55-62.

13. "Groundwater Monitoring/Remediation Suppliers", Pollution Engineering, September, 1993, p. 88.

14. Hand, D.W., Crittenden J.C., Harish A., Miller J.M., and Lykins B.W., "Designing Fixed-Bed Adsorbers to Remove Mixtures of Organics", Journal of the American Water Works Association, January 1989, pp 67-77.

15. Hand, D.W., Crittenden, J.C., and Thacker W.E., "Simplified Models For Design of Fixed-Bed Adsorption Systems", Journal of Environmental Engineering, ASCE, Vol. 110, No. 2, April, 1984, pp. 440-457.

16. Hand, D.W., Crittenden, J.C., and Thacker W.E., "User-Oriented Batch Reactor Solutions To The Homogenous Surface Diffusion Model", Journal of Environmental Engineering, ASCE, Vol. 109, No. 1, February, 1983, pp 82-101.

17. Hicks, B.N., and Caplin, J.A., "Bioremediation: A Natural Solution", Pollution Engineering, January 1993, pp 30-33.

18. Hiltz R.H., Project Summary-Design and Construction of a Mobile Activated carbon Regenerator System, EPA/600/S2-S6/015, August 1986.

19. Hutchinson D.H., and Robinson C.W., "A Microbial Regeneration Process For Granular Activated Carbon - I", Water Resources, Vol. 24, No. 10, 1990, pp 1209-1215.

20. Knox R.C., Canter L.W., Kincannon D.F., Stover E.L., and Ward C.H., Aquifer Restoration - State of the Art, Noyes Publications, Park Ridge, New Jersey, 1986.

21. Lewis N., Topudurti K., Welshans G., and Foster, R., "A Field Demonstration of the UV/Oxidation Technology to Treat Ground Water Contaminated With VOCs", Journal of Air & Waste Management Association, Vol.40, N0.4, April 1990, pp 540-547.

22. Liptak, Bela G., Environmental Engineers' Handbook, Volume 1 Water Pollution, Chilton Book Company, Raynor Pennsylvania 1974.

23. Love, T.O. and Inhoffer, W.R., Experience with Infrared Furnace For Reactivating Granular Activated Carbon, EPA, Cincinnati, Ohio, May 1979.

24. Means Building Construction Cost Data, R.S. Means Company, Inc., Construction Consultants & Publishers, Kingston, Ma.,1994.

25. Means Estimating Handbook , R.S. Means Company, Inc., Construction Consultants & Publishers, Kingston, Ma.,1990.

26. McGinnis, F.K. III, "Thermal Regeneration of Activated Carbon", Pollution Engineering, January 1984, pp 40-42.

27. "New Senate Superfund Plan", ENR, August 1994.

28. Nyer N.K., "Designing a Groundwater Treatment System", Pollution Engineering, March 1986, pp. 18-20.

29. Nyer E.K., and Morello M., "Trichloroethylene Treatment and Remediation", Groundwater Management Review, Spring 1993, pp 98-103.

30. Owano C. and Hardison L.C., "A Groundwater Remediation Plan", Water/Engineering and Management, October 1990, pp. 25-27.

31. Oxenford, J.L. and Lykins B.W., "Conference Summary: Practical Aspects of the Design and Use of GAC", Journal of the American Water Works Association, January 1991, pp. 58-64.

32. Petroleum Hydrocarbons and Organic Chemicals in Ground Water - Prevention, Detection and Restoration, National Water Well Association, Dublin, Ohio, 1985.

33. Pirbazari, M., Badriyha, B.N., and Miltner, R.J., "GAC Adsorber Design for Removal of Chlorinated Pesticides", Journal of Environmental Engineering, ASCE, Vol. 117, No. 1, January/February, 1991, pp. 80-99.

34. Process Design Manual For Carbon Adsorption, EPA 625/1-71-002a, Cincinnati Ohio, 1973.

35. Reid V.M., Wyatt K.W., and Horn J.A., "A New Angle On Ground-Water Remediation", Civil Engineering, April 1994, pp. 56-58.

36. Shirco Infrared Incineration System, Applications Analysis Report, EPA/540/A5-89/010, Cincinnati, Ohio, 1989.

37. Thomas, Alison, "Biological Destruction of Chlorinated Solvents", The Military Engineer, SAME, Vol. 86, No. 565, August/September, 1994, pp. 31-33.

38. Torma, A.E., "The Basics of Bioremediation", Pollution Engineering, June 1994, pp 46-48.

39. Travis C.C. and Doty C.B, "Can Contaminated Aquifers at Superfund Sites Be Remediated?", Environmental Science & Technology, Vol. 24, No. 10, 1990, pp 1464-1466.

40. Ultrox International Ultraviolet Radiation/Oxidation Technology, EPA/540/A5-89/012, September 1990,

41. Vembu, Kannan, "Exploring Wastewater Treatment Options", Pollution Engineering, May 1994.

42. Voice, T.C., Pak D., Zhao X., Shi J., and Hickley R.F, "Biological Activated Carbon In Fluidized Bed Reactors For The Treatment Of Groundwater Contaminated With Volatile Aromatic Hydrocarbons", Water Resources, Vol. 26, No. 10, pp. 1389-1401, 1992.

43. Yehaskel, A., Activated Carbon: Manufacture and Regeneration, Noyes data Corporation, Park Ridge, New Jersey, 1978.

Appendices

A. Operating Pressure Calculation
B. Table of Minimum Stanton Numbers Required for Constant Pattern Condition
C. Parameters For Empirical Equation That Describes Solutions To CPHSDM For a Fixed Bed Reactor
D. Example Calculation Using CPHSDM Solution
E. Pump/System Worksheets
F. Diagrams
G. Cost and Weight Estimate

A. Operating Vessel Pressure Calculation

From data in Appendix E for pump P4, expanded bed in series with fixed bed, the operating internal pressure in the adsorber vessels is calculated as follows:

$$P_2 = P_1 + Hp + Z_1 + V_1^2/2g - (Z_2 + V_2^2/2g + hL)$$

Where,

Hp = Pump Head = 39 Ft

P_1 = Pressure at surface of effluent tank = 0

Z_1 = Elevation at surface of effluent tank = 6 ft

$V_1^2/2g$ = Velocity head at surface of effluent tank = 0

P_2 = Internal pressure at surface of GAC vessel

Z_2 = Elevation at surface of GAC vessel = 20 ft

$V_2^2/2g$ = Velocity head at surface of GAC vessel = .2 ft

h_L = Sum of head losses from 1 to 2 = 8.8 ft

$$P_2 = 0 + 39 + 6 + 0 - (20 + .2 + 8.8) = 16 \text{ ft} = 7 \text{ psig}$$

Max. operating pressure at bottom of Vessel

For pressure test, fill entire column with water

P, Water pressure at tank bottom = Density X Depth

$P = 18 \text{ ft} \times 62.4 \text{ lb/ft}^3 = 1{,}123 \text{ lb/ft}^2 = 7.8 \text{ psig}$

Therefore, Max. operating pressure = 7 + 8.8 = **16 psig**

B. Table of Minimum Stanton Numbers Required for Constant Pattern Condition as Function of *Bi* for Various 1/n Values

The following table is a list of solutions presented by Hand and Crittenden.[15]

	$St_m = A_0(Bi) + A_1$			
1/n	**$0.5 \leq Bi \leq 10$**		**$10 \leq Bi \leq \infty$**	
	A_o	A_1	A_o	A_1
0.05	0.0210526	1.98947	0.22	0
0.10	0.0210526	2.18947	0.24	0
0.20	0.0421053	2.37895	0.28	0
0.30	0.105263	2.54737	0.36	0
0.40	0.231579	2.68421	0.50	0
0.50	0.526316	2.73684	0.80	0
0.60	1.15789	3.42105	1.50	0
0.70	1.78947	7.10526	2.50	0
0.80	3.68421	13.1579	5.00	0
0.90	6.31579	56.8421	12	0

C. Parameters For Empirical Equation That Describes Solutions To CPHSDM For a Fixed Bed Reactor

The following table is a partial list of solutions presented by Hand and Crittenden.[15]

1/n	Biot number	$T=A_0+A_1(C/C_0)^{A_2}+A_3/(1.01-(C/C_0)^{A_4})$					Equation Valid for C/C_0 between limits	
		A_0	A_1	A_2	A_3	A_4	Lower	Upper
.10	4.0	-2.337178	3.379926	0.043994	0.008650	.243412	0.02	0.99
.10	6.0	-2.407407	3.374131	0.041322	0.012552	0.196565	0.02	0.99
.10	10.0	-2.566414	3.370950	0.035003	0.019386	0.150788	0.02	0.99
.30	4.0	-0.565664	1.537833	0.084451	0.008808	0.139086	0.01	0.99
.30	6.0	-0.197077	1.118564	0.117894	0.011527	0.135874	0.01	0.99
.30	10.0	-.173358	1.000000	0.120311	0.015940	0.133973	0.01	0.99
.50	4.0	-.040800	0.982757	0.111618	0.008072	0.111404	0.01	0.99
.50	10.0	0.094602	0.754878	0.092069	0.009877	0.090763	0.01	0.99
.70	4.0	0.715269	0.307172	0.442104	0.004371	0.138251	0.01	0.99
.70	12.0	0.78940	0.243548	0.661599	0.004403	0.162595	0.01	0.99
.80	4.0	0.784576	0.239663	0.484422	0.003206	0.134987	0.01	0.99
.80	14.0	0.839439	0.188966	0.648124	0.003006	0.157697	0.01	0.99

D Example Calculation Using CPHSDM Solution

The following is an example of a constant pattern model solution for 1.2-dichloroethane at an EPA pilot plant located in Ohio. The parameters where found to be:

ρ_a = .722 gm/cm^3	R = .053 cm
ε = .449	K = 37.9 mg/g(L/mg)$^{.8316}$
D_s = 1.77 X 10^{-9} cm^2/s	1/n = .8316
ϕ = 1.0	q_e = 516 mg/g
Hyd. Loading Rate (H) = 4 gpm/ft^2	C_o = 23.2 mg/L
ρ (F-400 density) = 30.14 lb/ft^3	k_f = 3.29 X 10^{-3} cm/s

From equation 1:

$$D_g = \rho_a q_e (1-\varepsilon)/\varepsilon C_o \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$D_g = (.722 \text{ gm/cm}^3)(516 \text{ mg/g})(1-.449)/(.449)23.2 \text{ mg/L} = 19{,}700$$

From equation 2:

$$Bi = k_f R(1-\varepsilon)/D_g D_s \varepsilon\phi \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$Bi = \frac{(3.29 \text{ X } 10^{-3} \text{ cm/s})(.053 \text{ cm})(1-.449)}{(1.77 \text{ X } 10^{-9} \text{ cm}^2/\text{s})(19{,}700)(.449)(1.0)} = 6.14$$

From Appendix B:

$$St_m = A_o (Bi) + A_1 = 3.68421\ (6.14) + 13.1579 = 35.8$$

Then, using equation 7

$$EBCT_m = \tau_m/\varepsilon = St_m R\phi / k_f(1-\varepsilon) \quad \ldots\ldots\ldots \quad (7)$$

$$EBCT_m = (35.8(.053 \text{ cm}))/(3.29 \text{ X } 10^{-3} \text{ cm/s}(1-.449)) = 1047 \text{ s}$$

$$= 17.4 \text{ min.}$$

From Appendix C:

A_o = .784576 ; A_1 = .239663 ; A_2 = .484422 ; A_3 = .003206 ; A_4 = .134987

$T(Bi, 1/n, St_m) = A_o + A_1(C/C_o)^{A_2} + A_3/(1.01-(C/C_o)^{A_4})$

where, C/C_o= 100/5 = .05

$T = .784576 + .239663(.05)^{.484422} + .003206 /(1.01-(.05)^{.134987}) = .8501$

From equation 7, $\tau_m = \varepsilon(EBCT_m$= (.449) 17.4 min = 7.81 min

From equation 8,

$t_m = \tau_m(Dg +1)T$ ..... (8)

t_m = 7.81 min (19,701).8501 = 130,800 min = 90 days

Which is the elapsed time until C/C_o = .05

The carbon use per gal (G)= weight of carbon / gallons treated

weight of carbon = ρ (EBCT X H) (Q/H) = ρ(EBCT)Q

gallons treated = (Q) t_m

Rounding EBCT up to nearest 5 min = 20 minutes and replacing carbon when it reaches 70 % capacity (.7 X90 days = 65 days = 93,600 min)

Carbon use = $\rho(EBCT)/t_m$ = 30.14 lb/ft^3 (20 min)/ 93,600 min = .00644 lb/ft^3

(.00644 lb/ft^3)(ft^3 /7.48 gal) = 0.861 lb/1000 gal

Table 7.1 lists solutions for the CPHSDM for several contaminants using 70 % carbon capacity and rounding $EBCT_m$ to the nearest 5 min.

E. Pipes, Pumps, and Valves

Equations:

$NPSH_A$ = Suction Head - Vapor Pressure Head (-32 ft H_2O)

Reynolds Number = Velocity X diameter/ Kinematic Viscosity @ 50 °F

Friction Head Loss = $fLv^2/2gd$

Minor Head Loss = $kv^2/2g$

Head Loss in Carbon bed from Figure 7.3.

Head Loss in Carbon Slurry Line from Figure 3-25, Reference 34.

Whp = (Density X TDH X Q) /550

Bhp = Whp/Eff.

Where,

- f = friction factor from Moody diagram
- L = pipe length (ft)
- D = pipe diameter (ft)
- v = velocity (fps)
- g = gravitational constant (32.2 Ft/s^2)
- k = loss coefficient
- TDH = Total Dynamic Head (ft)
- Density = 62.4 lb/ft^3
- Q = Flow (cfs) = v X area (ft^2)

Pump 1: Backwash 12 gpm/ft^2 Q (gpm) = 60.00

Description	K	V (fps)	V^2/2g	d (ft)	f	L (ft)	Max. Head (ft)
Suction Side							
Vert. From Storage Tank		3.93	0.24		0		-2.00
2 Ball valves@ k=.1	0.2	3.93	0.24		0		0.05
2.5 inch PVC pipe		3.93	0.24	0.208	0.021	30	0.73
2-90 degree elbows@ k=.3	0.6	3.93	0.24		0		0.14
Total Suction Head (ft)	-1.08						

Discharge Side							
Vert. Infl. Tnk		3.93	0.24		0		10.00
6 Ball valves@k=.1	0.6	3.93	0.24		0		0.14
2.5 inch PVC pipe		3.93	0.24	0.208	0.021	60	1.46
8-90 degree elbows@ k=.3	2.4	3.93	0.24		0		0.58
Loss in GAC		3.93	0.24				15.00
Nozzels 40@k=1.5	60	3.93	0.24				14.42
Check Valve @k=15	15	3.93	0.24				3.61
Total Dischrge Head (ft)	45.20						

Summary	
Total Dynamic Head (ft)	**44.13**
NPSH available	**33.08**
Whp	**0.67**
Bhp (58% Eff.)	**1.15**
Reynolds Number	**58,000**
Friction factor	**0.021**
Capacity (cfs)	**0.13**

Pump 2: Booster Q (gpm) = 20.00

Description	K	V (fps)	V^2/2g	d (ft)	f	L (ft)	Head (ft-H20)
Suction Side							
From GAC pipe		3.63	0.20		0		-10.00
0 Ball valves@k=10	0	3.63	0.20		0		0.00
1.5 inch PVC pipe		3.63	0.20	0.125	0.023	0	0.00
0-90 degree elbows@k=.3	0	3.63	0.20		0		0.00
Loss in GAC		3.63	0.20				0.00
Gac support screen	0	3.63	0.20				0.00
Total Suction Head (ft)	-10						

Discharge Side							
Vert. Storage Tank		3.63	0.20		0		15.00
3 Ball valves@k=.1	0.3	3.63	0.20		0		0.06
1.5 inch PVC pipe		3.63	0.20	0.125	0.023	30	1.13
3-90 degree elbows@k=.3	0.9	3.63	0.20		0		0.18
Check Valve @k=15	15	3.63	0.20				3.07
Total Dischrge Head (ft)	19.45						

Summary	
Total Dynamic Head (ft)	9.447402158
NPSH available	42
Whp	0.047765183
Bhp (58% Eff.)	0.082353765
Reynolds Number	32,000
Friction factor	0.023
Capacity (cfs)	0.04456328

Pump 3: Carbon Supply Q (gpm) = 40.00

Description	K	V (fps)	V^2/2g	d (ft)	f	L (ft)	Head (ft-H20)
Suction Side							
From Storage Tank		4.07	0.26		0		-1.00
2- rotary valves@ k=10	20	4.07	0.26		0		5.14
2 inch SS pipe (5ft/100ft)		4.07	0.26	0.167	0.05	20	1.00
2-90 degree Long Rad. elb.	0.6	4.07	0.26		0		0.15
Total Suction Head (ft)	5.30						

Discharge Side							
To GAC Vessle		4.07	0.26		0		21.50
3- rotary valves@(k=10)	30	4.07	0.26		0		7.71
2 inch SS pipe (5ft/100ft)		4.07	0.26	0.167	0.05	25	1.25
2-90 degree elbows@(k=.3)	0.6	4.07	0.26		0		0.15
check valve	15	4.07	0.26				3.86
Total Dischrge Head (ft)	34.47						

Summary	
Total Dynamic Head (ft)	39.77
NPSH available	26.70400019
Whp	0.31
Bhp (55% Eff.)	0.533340269
Capacity (cfs)	0.08912656

Pump 4: Influent Q (gpm) = 20.00

Description	K	V (fps)	V^2/2g	d (ft)	f	L (ft)	Head (ft-H20)
Suction Side							
From Storage Tank		3.63	0.20		0		-2.00
3 Ball valves@ k=.1	0.3	3.63	0.20		0		0.06
1.5 inch PVC pipe		3.63	0.20	0.125	0.026	20	0.85
3-90 degree elbows	0.9	3.63	0.20		0		0.18
Nozzels 40@k=1.5	0	3.93	0.24				0.00
Gac support screen	0	3.63	0.20				0.00
Total Suction Head (ft)	-0.902482709						

Discharge Side							
Vert to S. Tank		3.63	0.20		0		10.00
8-Ball valves@(k=.1)	0.8	3.63	0.20		0		0.16
1.5 inch PVC pipe		3.63	0.20	0.125	0.026	24	1.02
8-90 degree elbows@(k=.3)	2.4	3.63	0.20		0		0.49
Loss in GAC (Figure)		3.63	0.20				10.60
Nozzels 40@k=1.5	60	3.93	0.24				14.42
Check Valve @k=15	15	3.63	0.20				3.07
Total Dischrge Head (ft)	39.77						

Summary	
Total Dynamic Head (ft)	38.87
NPSH available	32.90248271
Whp	0.20
Bhp (55% Eff.)	0.338818787
Reynolds Number	3.2E+4
Friction factor	0.026
Capacity (cfs)	0.04456328

Pumps 5 & 6: Influent Q (gpm) = 20.00

Description	K	V (fps)	V^2/2g	d (ft)	f	L (ft)	Head (ft-H20)
Suction Side							
From Storage Tank		3.63	0.20		0		-2.00
3 Ball valves	0.3	3.63	0.20		0		0.06
1.5 inch PVC pipe		3.63	0.20	0.125	0.026	30	1.28
2-90 degree elbows	0.6	3.63	0.20		0		0.12
Loss in GAC		3.63	0.20				0.00
Nozzels 40@k=1.5	0	3.93	0.24				0.00
Total Suction Head (ft)	-0.54						

Discharge Side							
Vert. To Booster Thru GAC		3.63	0.20		0		0.00
5-Ball valves@(k=.1)	0.5	3.63	0.20		0		0.10
1.5 inch PVC pipe		3.63	0.20	0.125	0.026	20	0.85
6-90 degree elbows@(k=.3)	1.8	3.63	0.20		0		0.37
Loss in GAC (Figure)		3.63	0.20				5.65
Nozzels 40@k=1.5	60	3.93	0.24				14.42
Check Valve @k=15	15	3.63	0.20				3.07
Total Dischrge Head (ft)	24.47						

Summary	
Total Dynamic Head (ft)	23.93
NPSH available	32.53800868
Whp	0.12
Bhp (55% Eff.)	0.20858411
Reynolds Number	32,000
Friction factor	0.026
Capacity (cfs)	0.04456328

F. Drawings

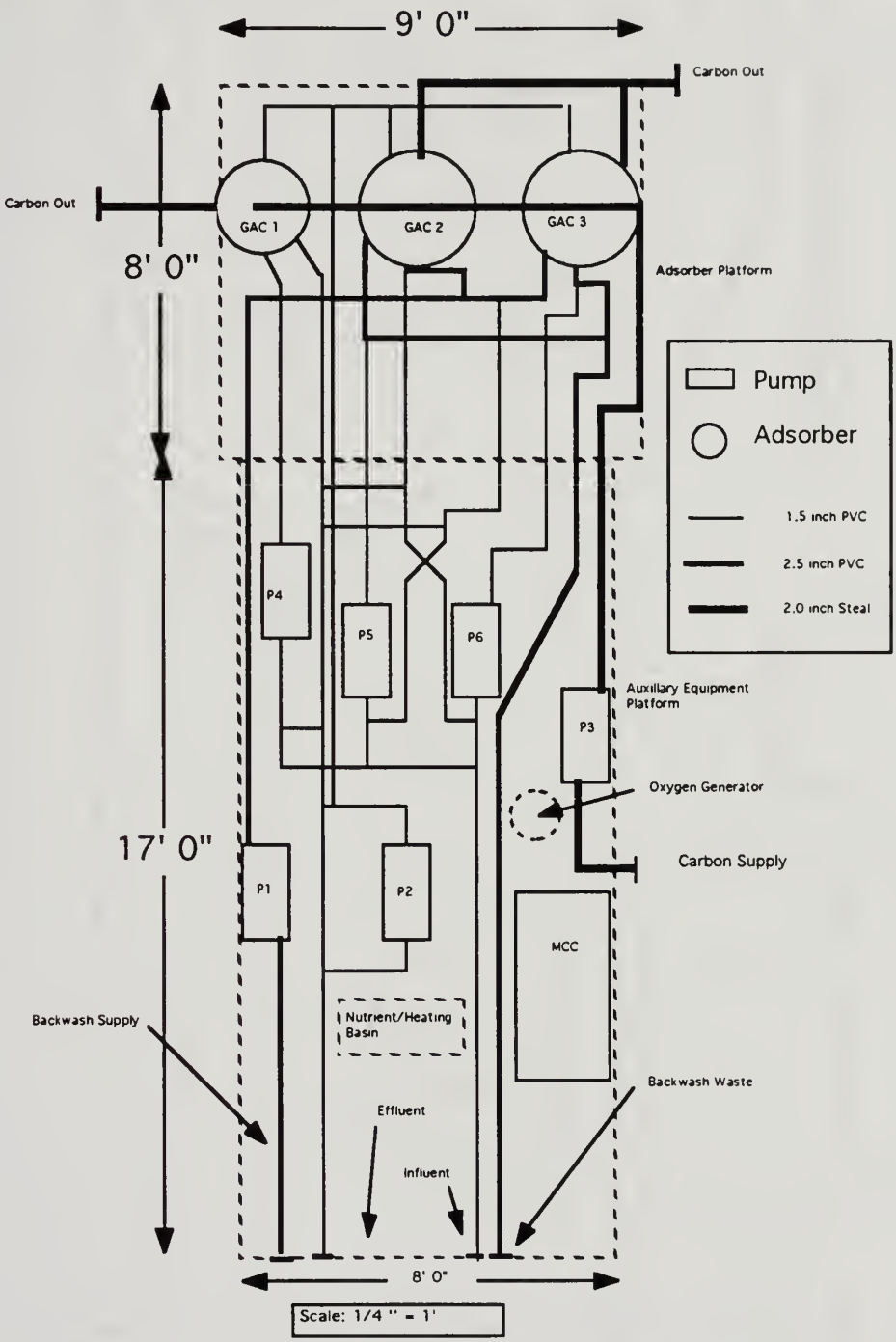
Drawing M-1, Flow Diagram Combined Sections
Drawing M-2, Flow Diagram Auxiliary Section Detail
Drawing M-3, Flow Diagram Adsorber Section Detail

Drawing A-1, Adsorber Vessel
Drawing A-2, Adsorber Vessel End Assembly Detail

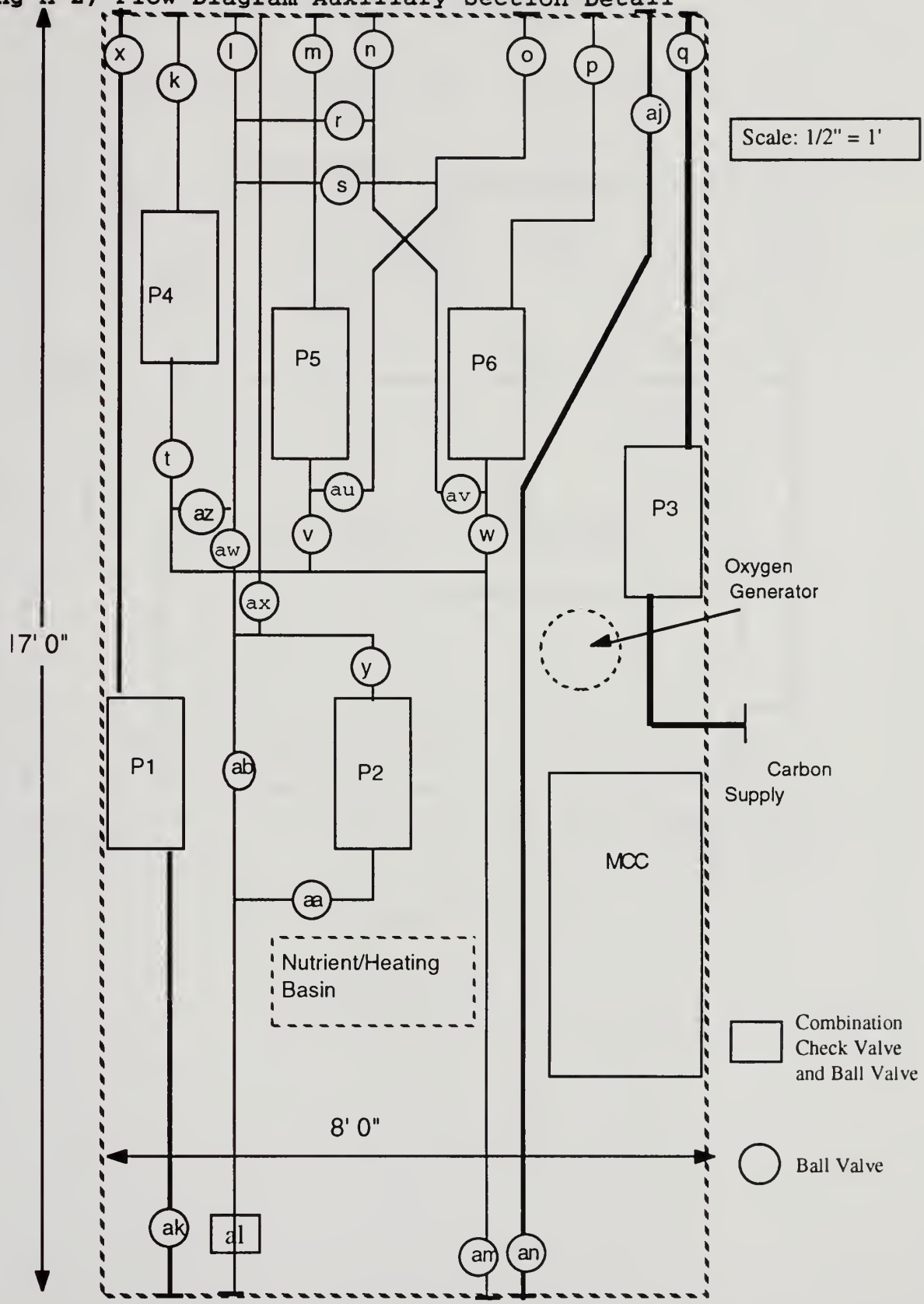
Drawing S-1, Structural Plan View Combined Sections
Drawing S-2, Structural Plan View Skid Detail
Drawing S-3, Structural Side View Adsorber Section
Drawing S-4, Structural Side View Auxiliary Section
Drawing S-5, Structural End View Auxiliary Section
Drawing S-6, Structural End View Adsorber Section

Drawing E-1, Electrical Layout

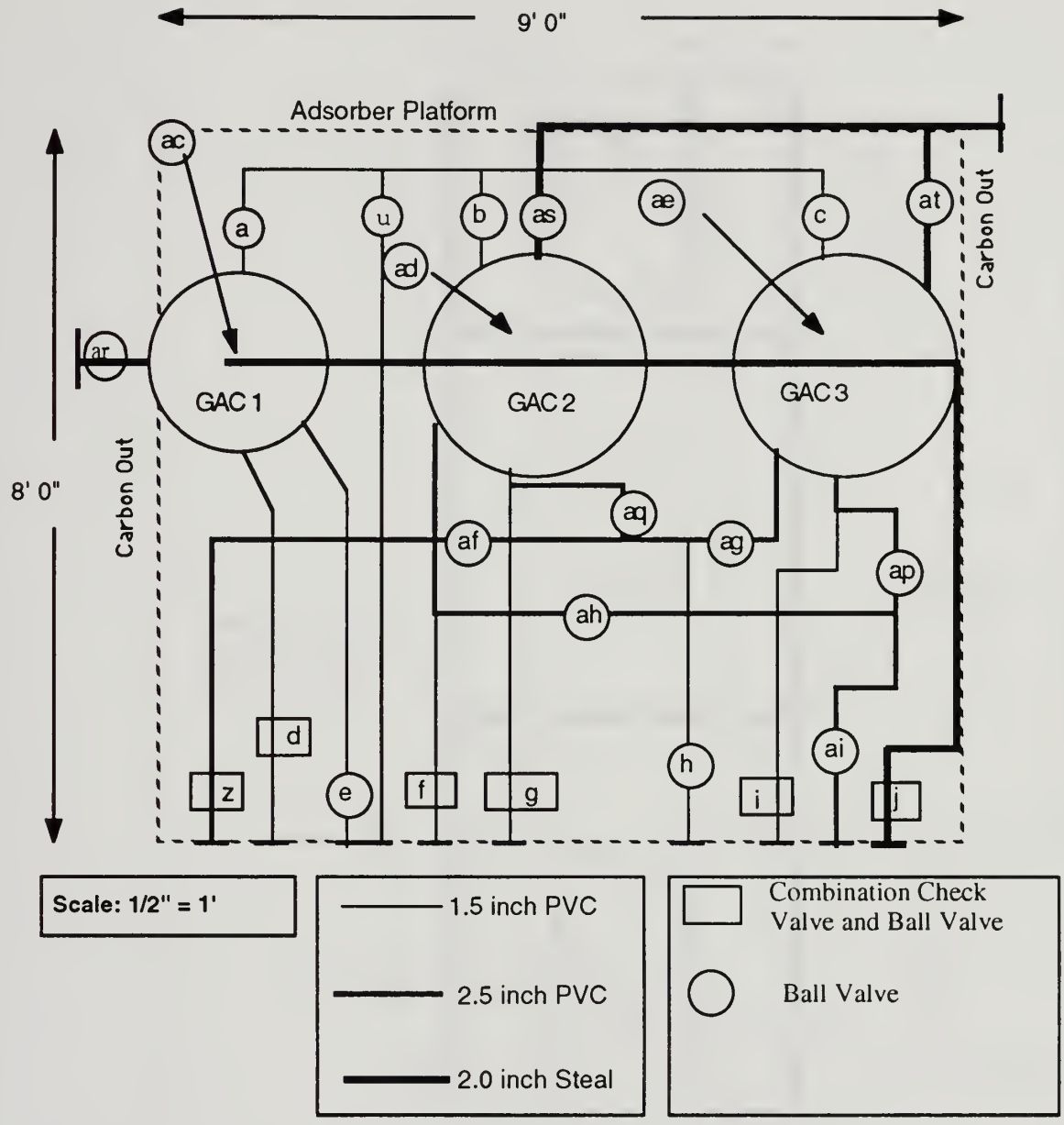
Drawing M-1, Flow Diagram Combined Sections



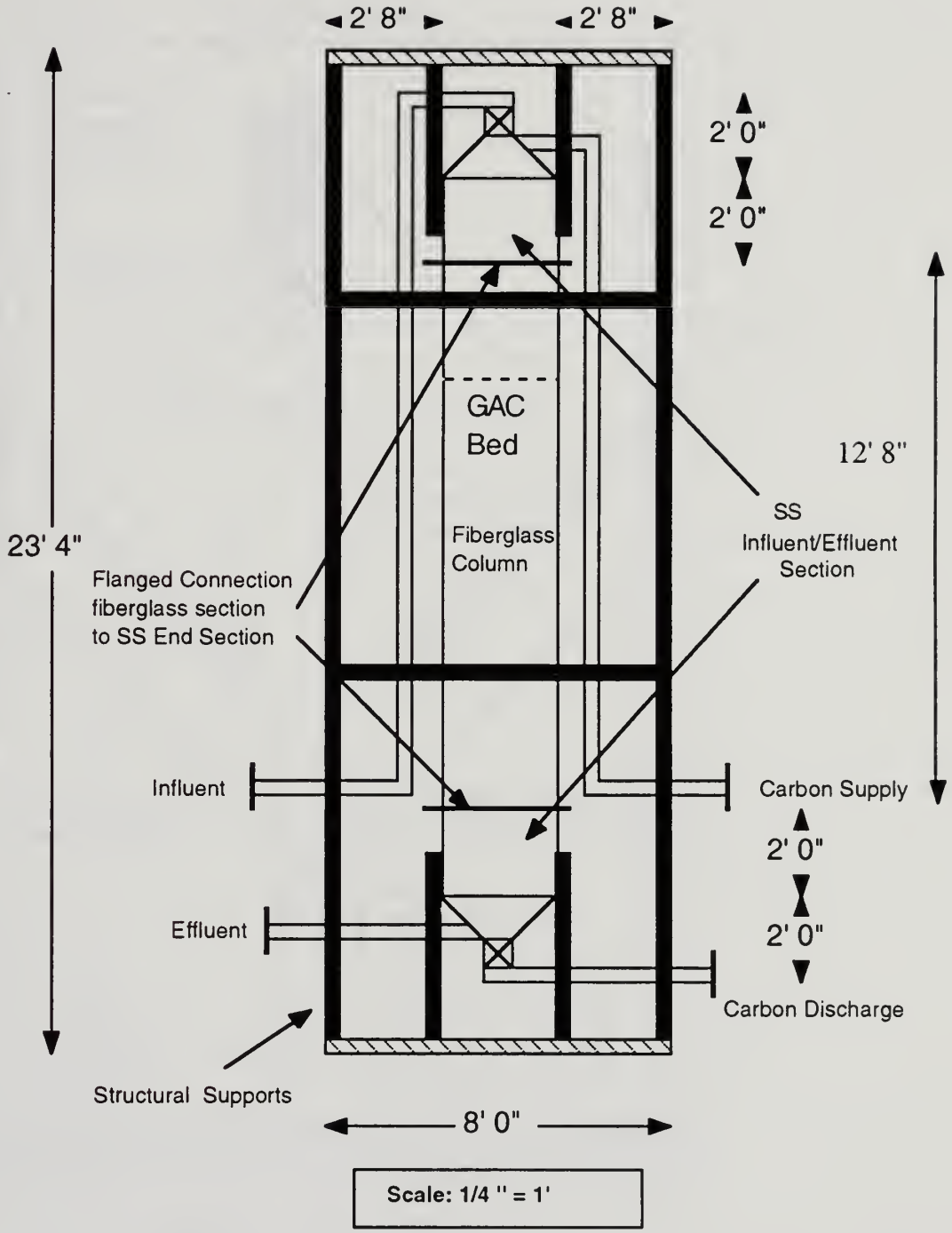
Drawing M-2, Flow Diagram Auxiliary Section Detail



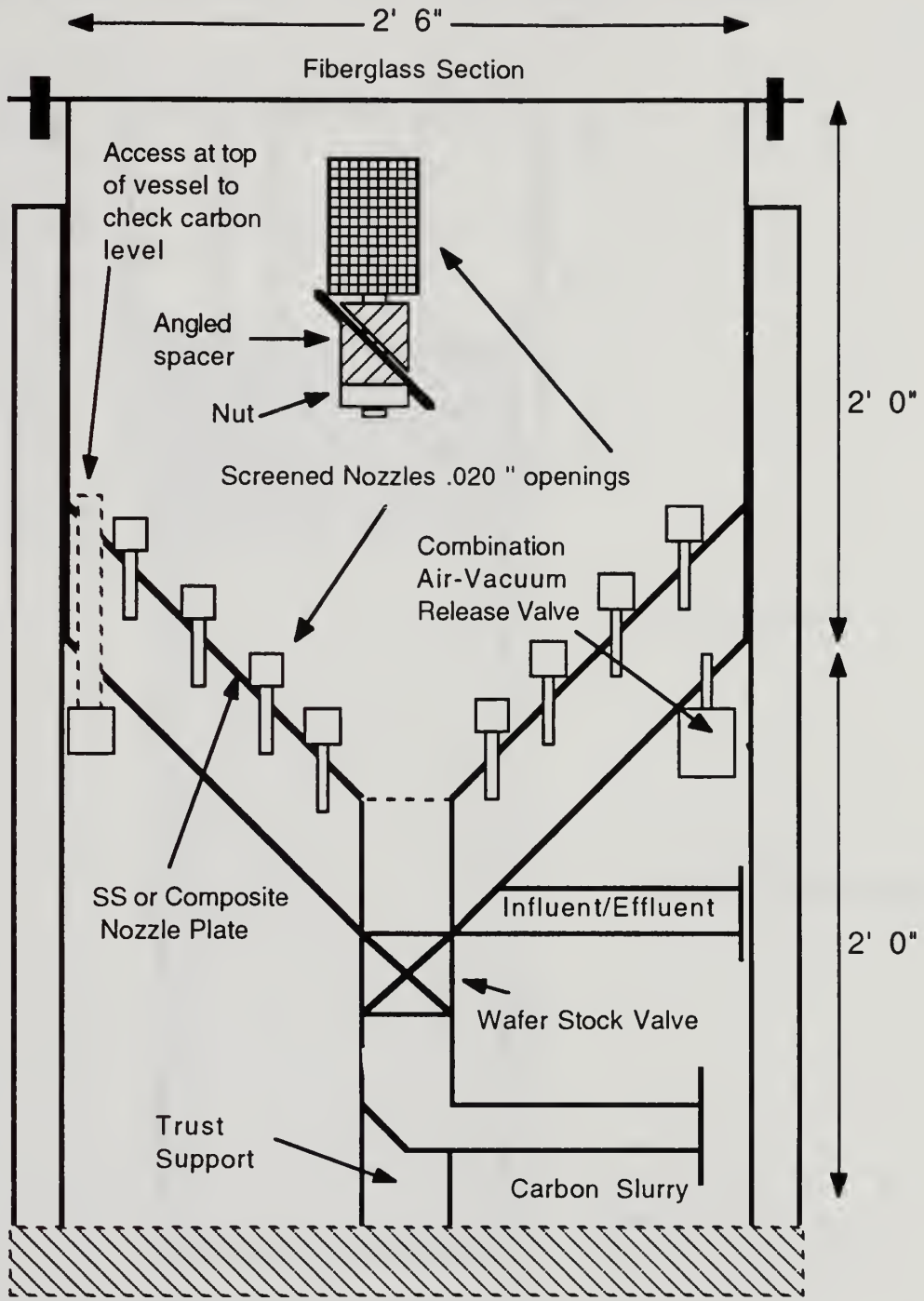
Drawing M-3, Flow Diagram Adsorber Section Detail



Drawing A-1, Adsorber Vessel

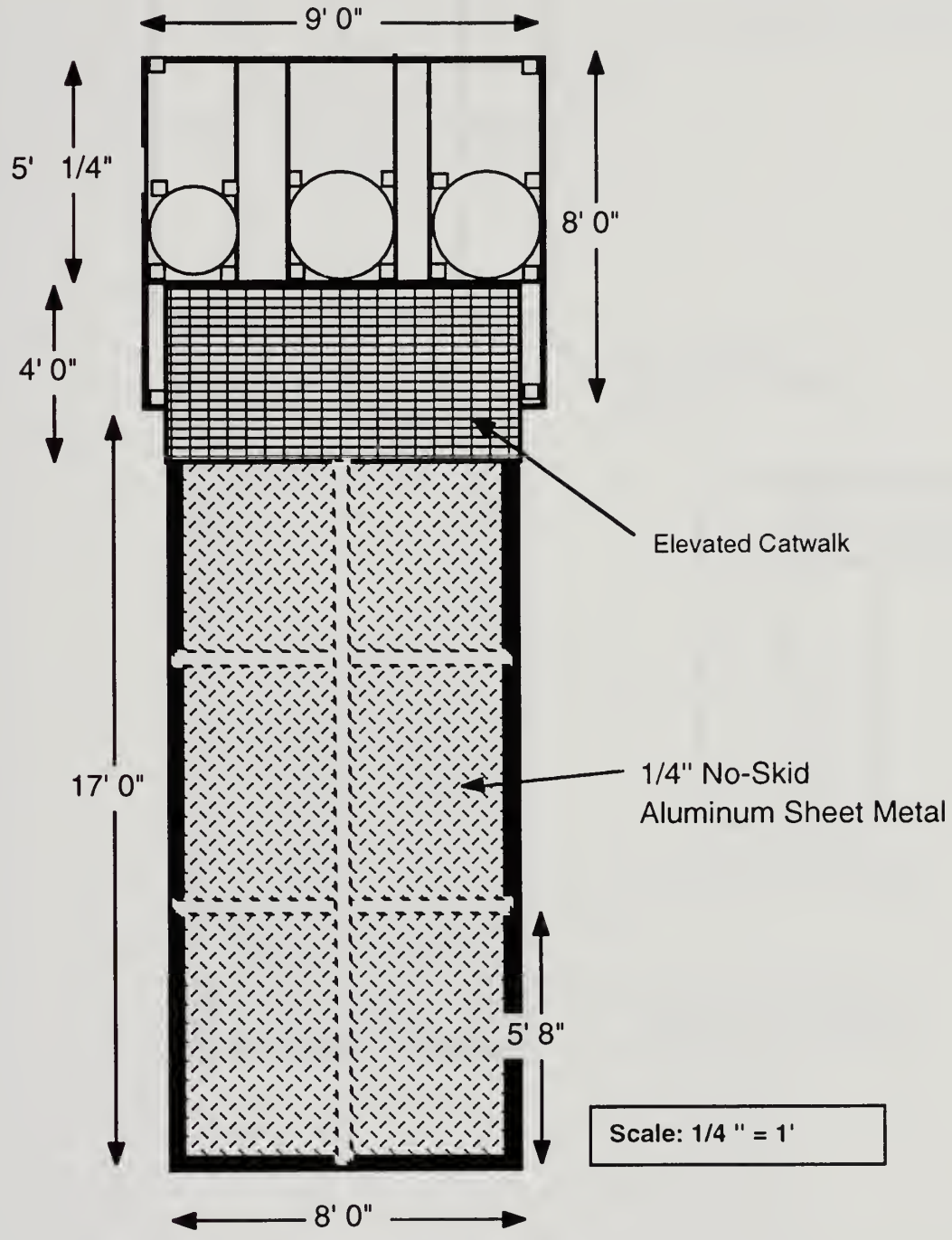


Drawing A-2, Adsorber Vessel End Assembly Detail

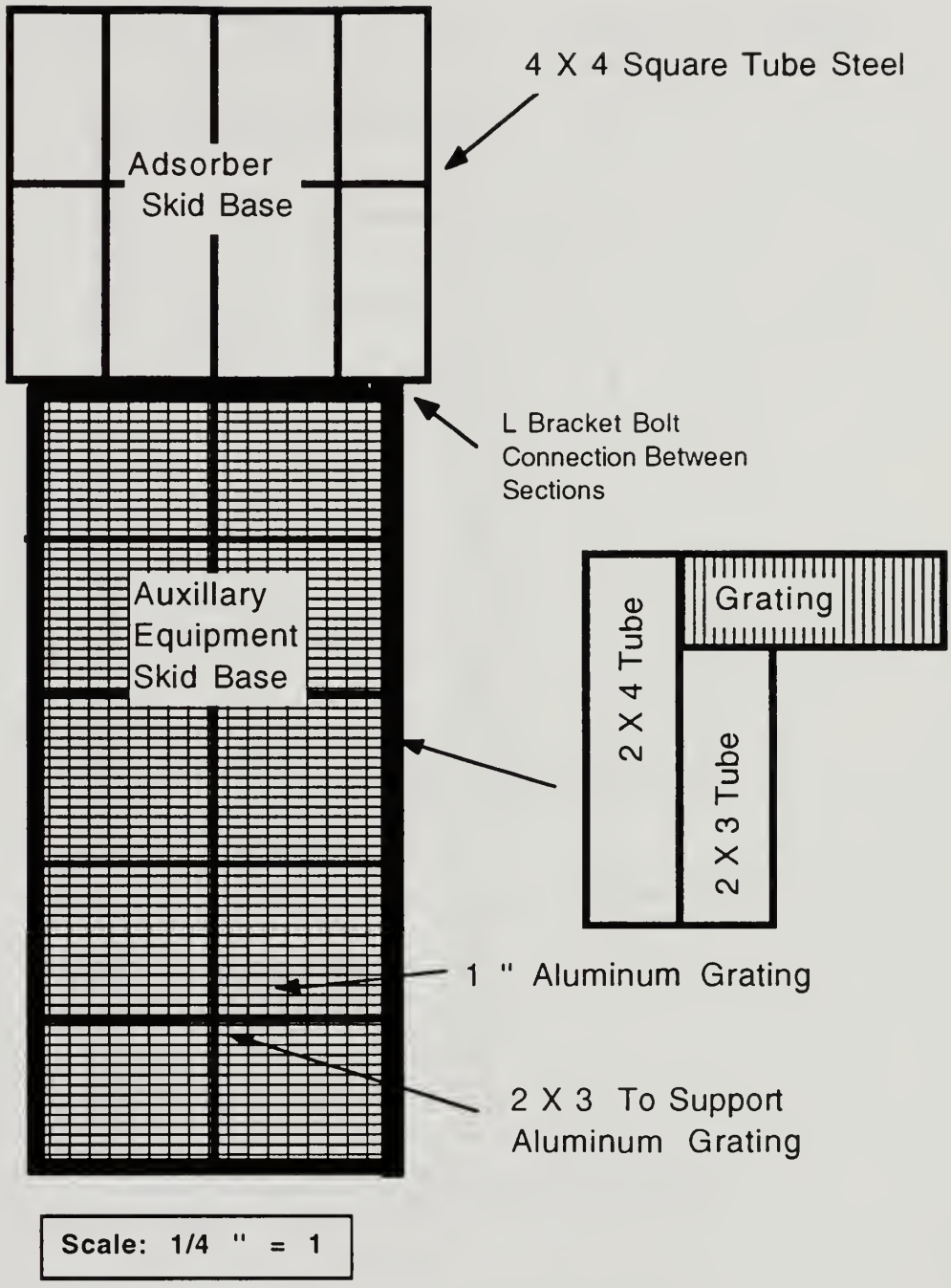


Scale: 1 1/2 " = 1'

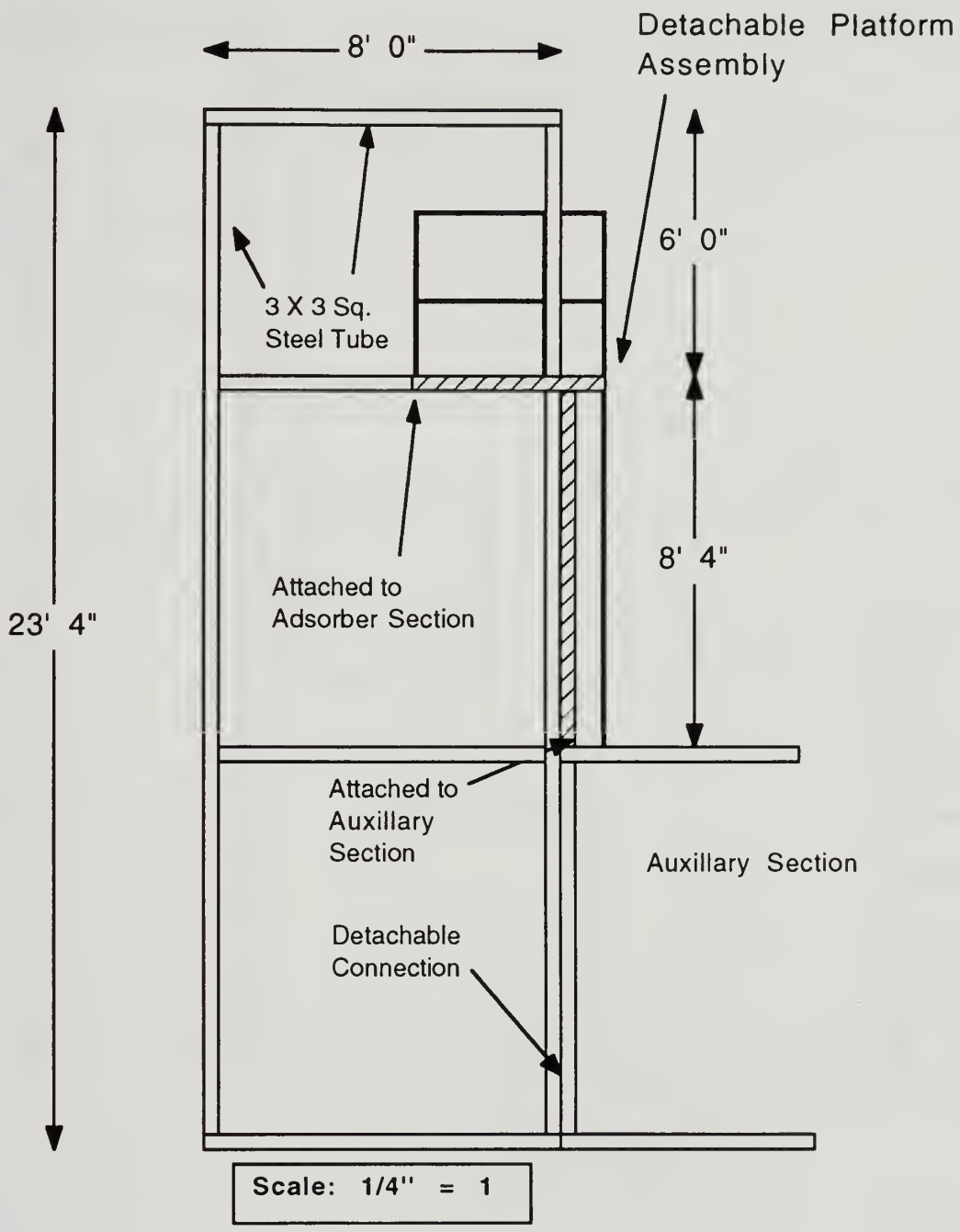
Drawing S-1, Structural Plan View Combined Sections



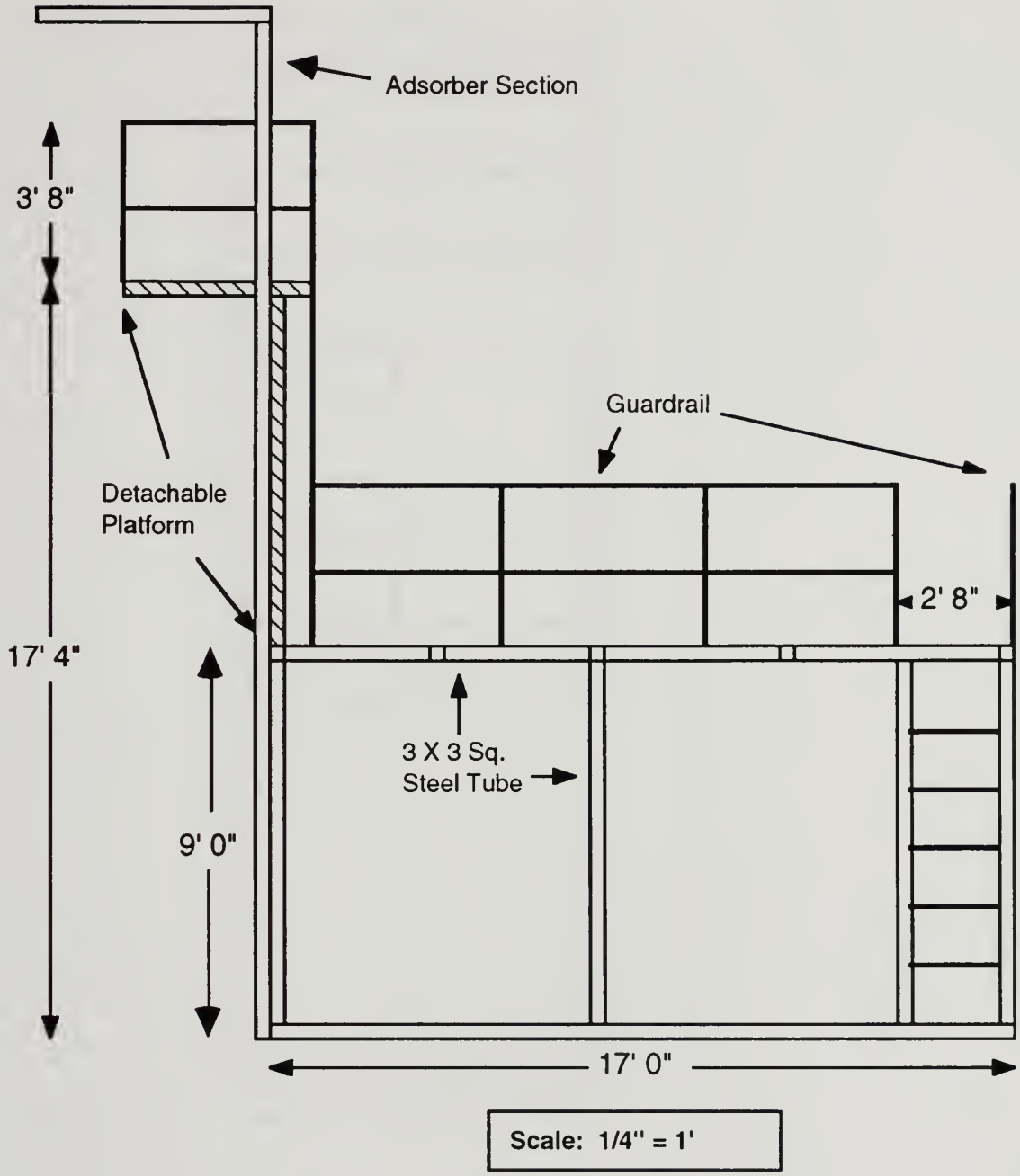
Drawing S-2, Structural Plan View Skid Detail



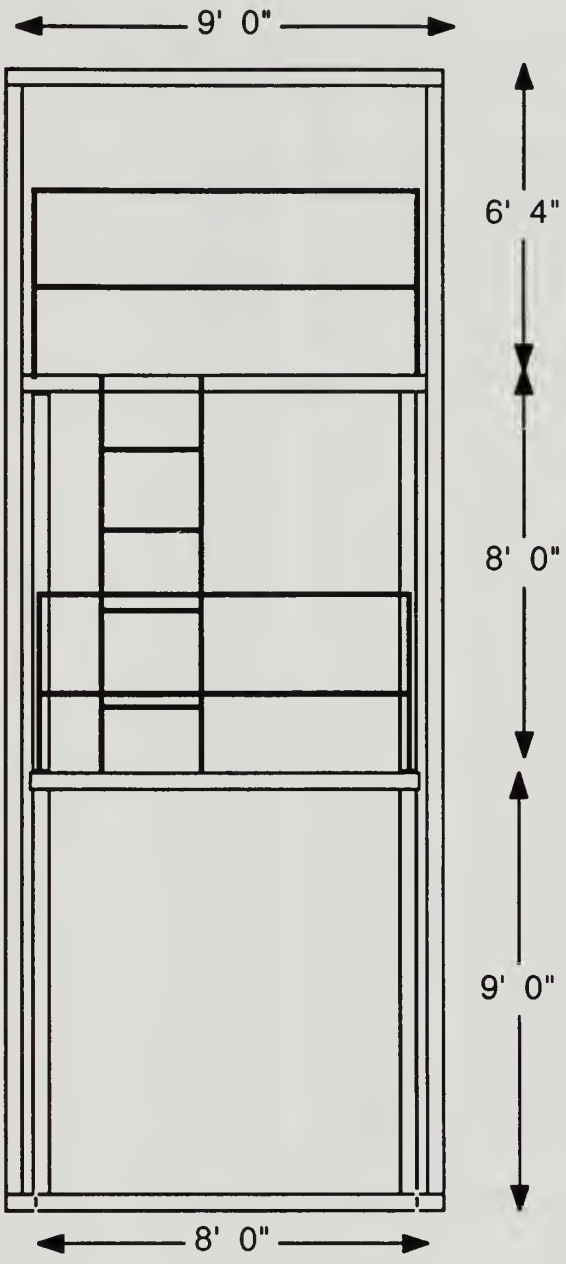
Drawing S-3, Structural Side View Adsorber Section



Drawing S-4, Structural Side View Auxiliary Section

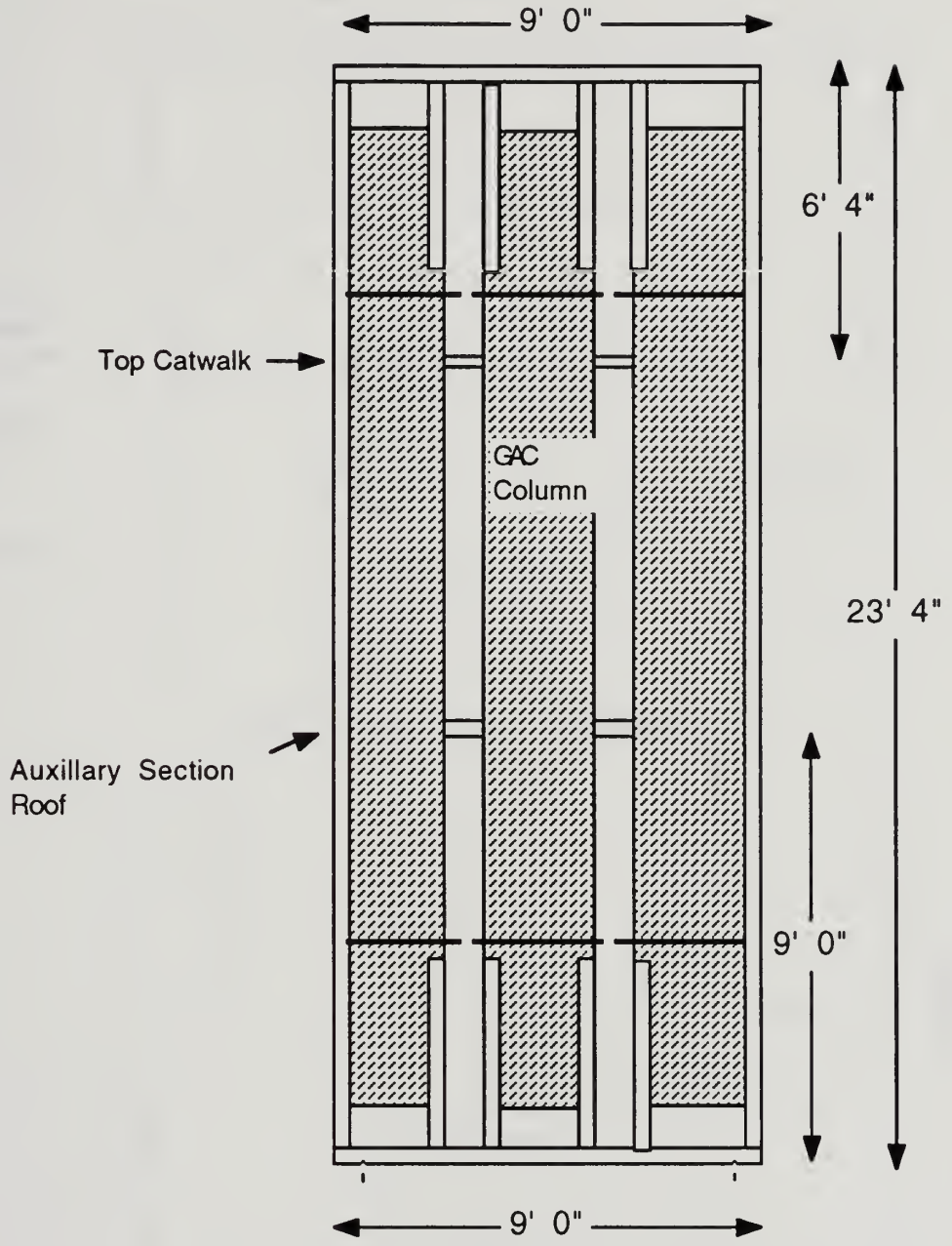


Drawing S-5, Structural End View Auxiliary Section



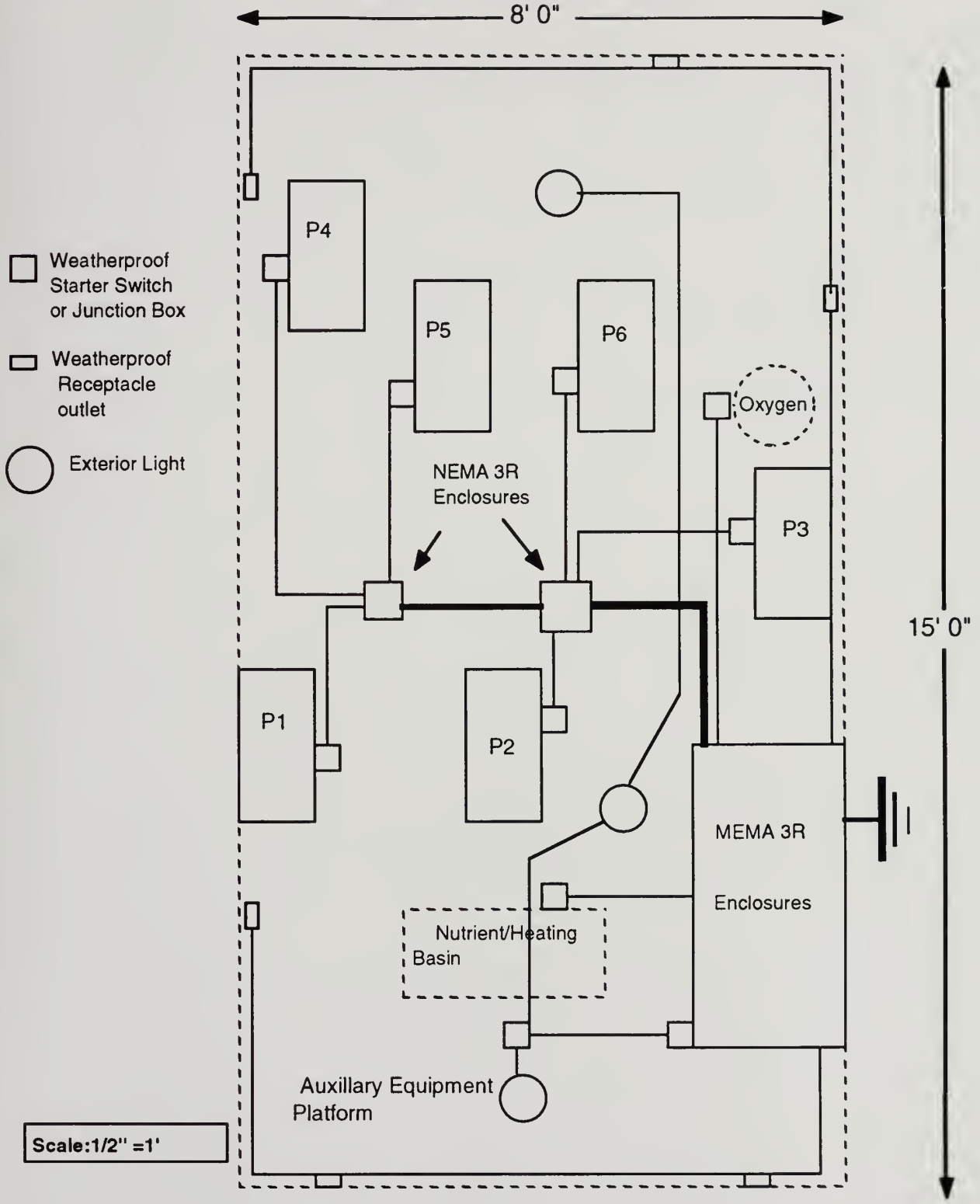
Scale: 1/4" = 1

Drawing S-6, Structural End View Adsorber Section



Scale: 1/4" = 1

Drawing E-1, Electrical Layout



G. Cost and Weight Estimate

Cost Estimate Work Sheet **GAC VESSELS**

		Materials			Labor					Weight
Description	Unit	Quantity	$/Unit	Total	MH/Unit	Manhours	$/MD	Total	Total $	(lb)
AC	lb	5000	1.2	6000	0	0		0	6000	5000
				0		0		0	0	
				0		0		0	0	
affer Stock Valves	ea	6	230	1380	0.6	3.6	25	90	1470	150
				0		0		0	0	
				0		0		0	0	
ozzels	ea	40	45	1800	0.2	8	25	200	2000	12
ozzel Support Plate	ea	6	200	1200	12	72	25	1800	3000	120
sorber Fiberglass Section	ea	3	500	1500	20	60	25	1500	3000	275
				0		0		0	0	
dsorber Steal End Section	ea	6	950	5700	20	120	25	3000	8700	6000
				0		0		0	0	
elding	LS			35		4	23	92	127	
				0		0		0	0	
isc. SS Bolts and Plumbing				235		6	25	150	385	25
				0		0		0	0	
				0		0		0	0	
ampling ports	ea	12	6	72	0.25	3	7	21	93	8
				0		0		0	0	
				0		0		0	0	
aint (Wisconsin Plasite 4020)	gal	4	300	1200	4	16	7	112	1312	20
ssembly	Lump	1		0	80	80	12	960	960	
				0		0		0	0	
				0		0		0	0	
ub-total				**19122**		**372.6**		**7925**	**27047**	**11610**
are Total				46674.9		847.795		13173	59848.07	18095
axes 7% on materials									3267.243	
rofit 15 % of total									8977.211	
otal									**72092.52**	

Cost Estimate Work Sheet **STRUCTURAL**

		Materials			Labor					Weight
Description	Unit	Quantity	$/Unit	Total	MH/Unit	Manhours	$/MH	Total	Total $	(lb)
				0		0		0	0	
				0		0		0	0	
x 4 Tube Steel, 8.81 lb/LF,	ea	5	60	300		0		0	300	440
! ft. section										
x 3, 7.11 lb/LF, 12 ft sections	ea	5	43	215		0		0	215	356
x 3, 8.81 lb/LF, 12 ft. section	ea	26	90	2340		0		0	2340	444
x 4 ,12.21 lb/LF. 12 ft sections	ea	19	115	2185		0		0	2185	2750
				0		0		0	0	
ıdder, steel w/o cage	VLF	16	25	400	0.38	6.08	7	42.56	442.56	80
				0		0		0	0	
				0		0		0	0	
uard Rail, Alum. 2 rail	LF	80	14.5	1160	0.2	16	7	112	1272	200
1/4" dia. w 4 " kick plate				0		0		0	0	
				0		0		0	0	
				0		0		0	0	
uminum Grating 2.1 lb/SF	SF	175	10.95	1916.25	0.03	5.25	7	36.75	1953	368
				0		0		0	0	
4 " Aluminum sheet plate,	lb	700	0.65	455	0	0	7	0	455	700
o-skid, 5 lb/SF				0		0		0	0	
				0		0		0	0	
isc Bolts				35		4	7	28	63	10
				0		0		0	0	
/elding	LF	75	0.41	30.75	0.1	7.5	23	172.5	203.25	
Fabrication set up & assembly	LS			0		25	23	575	575	
				0		0		0	0	
lisc. Assemble				200	8	8	7	56	256	100
				0		0		0	0	
aint:				0		0		0	0	
rimer	gal	3	40	120	3	9	12	108	228	
namel	gal	3	60	180	3	9	12	108	288	15
ub-total				**9537**		**242.17**		**1239**	**10775.81**	**5463**

Cost Estimate Work Sheet **MECHANICAL**

		Materials			Labor					Weight
Description	Unit	Quantity	$/Unit	Total	MH/Unit	Manhours	$/Mh	Total	Total $	(lb)
				0		0		0	0	
ump P1 (1.25 hp), 2.5 " size	ea	1	1150	1150	5	5	25	125	1275	75
				0		0		0	0	
ump P2 (1/10 hp), 1.5 "	ea	1	535	535	2.5	2.5	25	62.5	597.5	20
				0		0		0	0	
ump P3 (1/2 hp) rubber impeller	ea	1	980	980	3	3	25	75	1055	30
"				0		0		0	0	
ump P4 (4/10hp), 1.5 "	ea	1	560	560	3.1	3.1	25	77.5	637.5	35
				0		0		0	0	
ump P5 & P6 (2/10 hp), 1.5"	ea	2	475	950	2.7	5.4	25	135	1085	48
				0		0		0	0	
VC Pipe w/ hangers & couplings:				0		0		0	0	
5 inch Sch. 40	LF	75	2.81	210.75	0.286	21.45	12	257.4	468.15	35
5 inch	LF	220	1.83	402.6	0.22	48.4	12	580.8	983.4	50
				0		0		0	0	
inch SS pipe	LF	35	14.4	504	0.28	9.8	25	245	749	35
				0		0		0	0	
heck Valves, bronze				0		0	12	0	0	
5 "	ea	5	45		0.615		12			15
5 "	ea	1	158	158	1.07	1.07		0	158	5
all Valves, PVC				0		0		0	0	
5 "	ea	25	21.5	537.5	0.4	10	12	120	657.5	38
all Valve, Bronze										
5 "	ea	12	43	516	0.76	9.12	12	109.4	625.44	30
ressure/vacuum relief valve	ea	6	38	228	0.5	3	12	36	264	
				0		0	25	0	0	
lisc.Plumbing (Elbows, tees,)	LS			230		6	12	72	302	25
				0		0		0	0	
lange Bolts & Gaskets	LS			100		4	12	48	148	15
ensor wiring	LF	200	0.2	40	0.02	4	25	100	140	
Pressure sensors	ea	3	475	1425	0.5	1.5	12	18	1443	45
ressure recorder	ea	3	259	777	2	6	25	150	927	
Flow Meters	ea	6	325	1950	0.5	3	12	36	1986	35
low Recorder/monitor	ea	6	433	2598	1	6	25	150	2748	
				0		0		0	0	
ub-total				**13851.9**		**152.34**		**2398**	**16249.49**	**536**

Cost Estimate Work Sheet **ELECTRICAL**

		Materials			Labor					Weight
Description	Unit	Quantity	$/Unit	Total	MH/Unit	Manhours	$/MD	Total	Total $	(lb)
EMA -3R Enclosure										
x 36 x 12	ea	2	350	700	4	8	12	96	796	25
				0		0		0	0	
d. Rod 10', 3/4"	ea	1	25	25	1.5	1.5	27	40.5	65.5	15
				0		0		0	0	
d. Wire	LF	20	0.25	5	0.2	4	27	108	113	20
				0		0		0	0	
00 amp Panel board, 1 pole,	ea	1	800	800	9	9	27	243	1043	50
10 circuits & main breaker				0		0		0	0	
2 "Flex conduit BX #14, 3 wire	CLF	0.2	38	7.6	3.6	0.72	12	8.64	16.24	20
2 " conduit Rigid Galv.	LF	95	1.25	118.75	0.047	4.465	12	53.58	172.33	30
" conduit	LF	50	2.1	105	0.07	3.5	12	42	147	25
5 " conduit	LF	20	3.2	64	0.089	1.78	12	21.36	85.36	35
				0		0		0	0	
terior Lights,200 watt,	ea	3	325	975	2	6	27	162	1137	30
xp. proof				0		0		0	0	
R Recptacles	ea	8	20	160	0.9	7.2	12	86.4	246.4	10
				0		0		0	0	
EMA 3R				0		0		0	0	
n/off/auto switch	ea	6	40	240	0.9	5.4	27	145.8	385.8	15
ll boxes, NEMA 3R, 8x8x6	ea	2	135	270	2.2	4.4	12	52.8	322.8	14
				0		0		0	0	
ire, # 14, copper, THHN	CLF	6	4.25	25.5	0.61	3.66	12	43.92	69.42	120
ire, # 12, copper, THHN	CLF	2	6.1	12.2	0.73	1.46	12	17.52	29.72	50
				0		0		0	0	
X 4 box w/WR cover	ea	2	8	16	1.3	2.6	12	31.2	47.2	2
mp Auto Shut Off:				0		0		0	0	
at switch	ea	2	145	290	3.5	7	27	189	479	
to disconnect/ pump circuits	ea	2	125	250	2.5	5	27	135	385	
isc. Elec.	ea	1	100	100	5	5	27	135	235	25
				0		0		0	0	
				0		0		0	0	
				0		0		0	0	
ub-total				4164.05		80.685		1612	5775.77	486

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY CA 93943-5101

DUDLEY KNOX LIBRARY
3 2768 00307269 5